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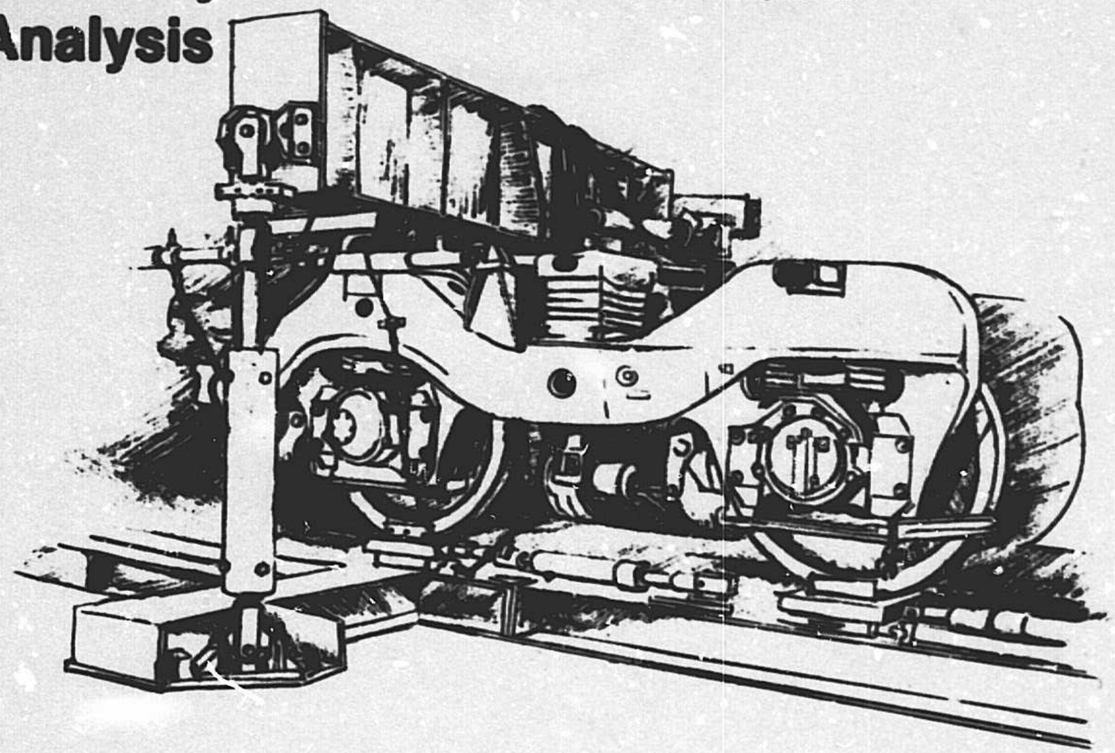
Industry Review

1 December 1981

Locomotive Dynamic Characterization Test/Analysis



MARTIN MARIETTA

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Locomotive Dynamic Characterization Test/Analysis

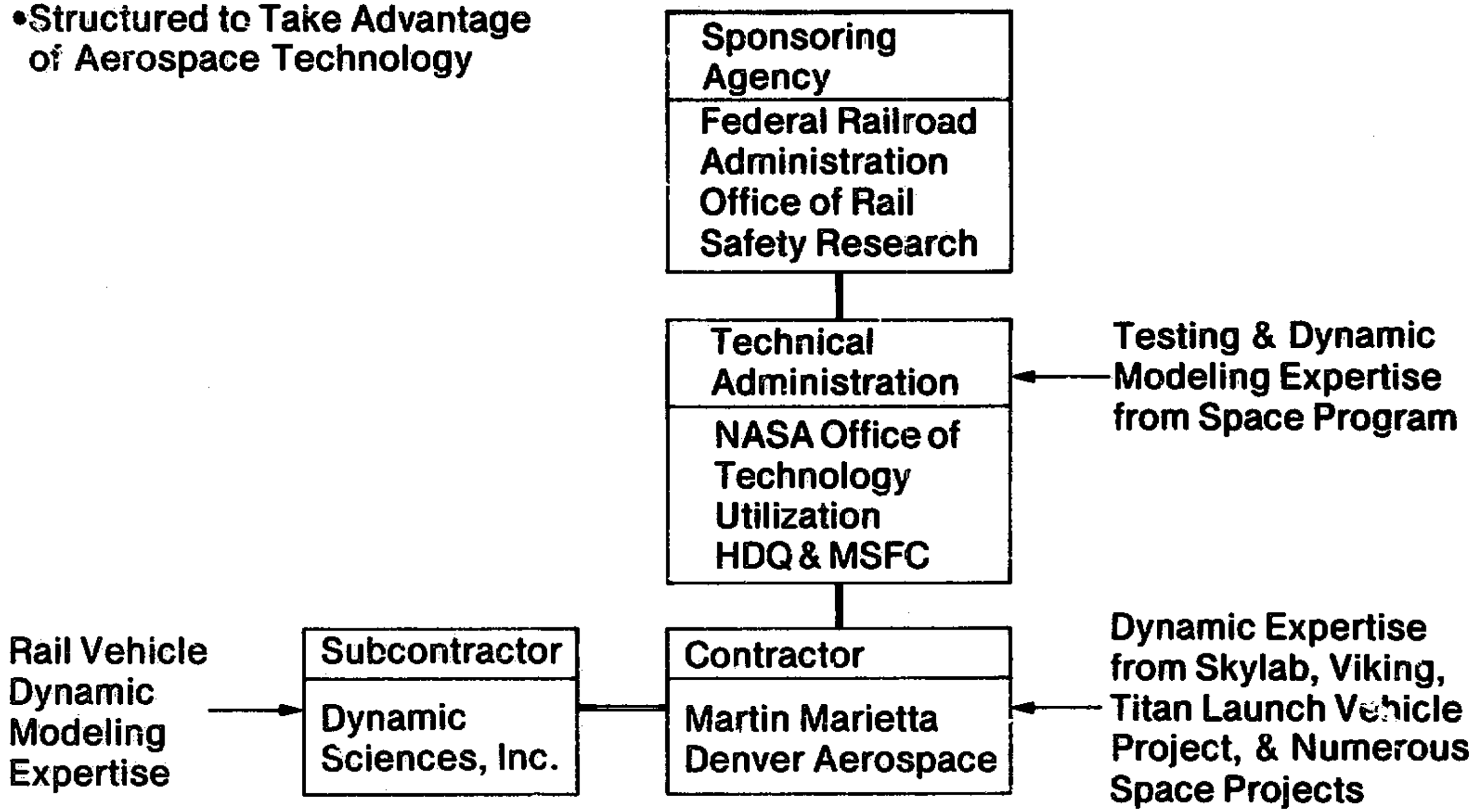
Martin Marietta Corporation
Denver Aerospace
Denver, Colorado 80201

Contract Administration

In June of 1976 the Federal Railroad Administration (FRA) and the National Aeronautical and Space Administration (NASA) initiated a joint program to study locomotive dynamics, with the goal to improve locomotive operational safety. The contract was organized to take advantage of aerospace technology.

Contract Administration

- Joint Program: NASA-MSFC - Office of Technology Utilization
  FRA - Office of Rail Safety Research
- Structured to Take Advantage of Aerospace Technology



Objective

This contract was conducted in two phases. During Phase I we established (and refined) a test methodology to define the suspension characteristics of locomotive trucks. Six three-axle trucks were tested during Phase I, establishing a data base for future analyses and evaluations.

Phase II of the contract included the testing of two two-axle locomotives and the development of an analytical methodology for evaluating locomotive operational safety. The analytical approach was based on using the experimentally determined truck parameters from the test program.

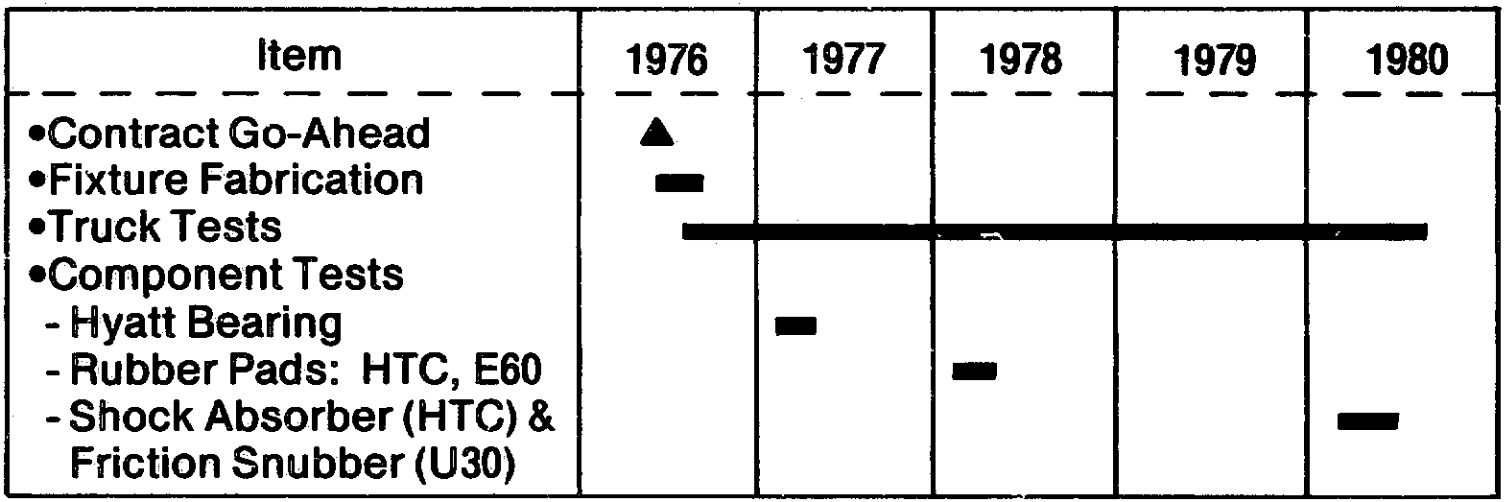
Contract Objective

Establish a Methodology for Evaluating Locomotive Operational Safety Using an Analytical Approach Based on Experimentally Determined Truck Parameters

Testing Overview

Since contract initiation in mid-1976, eight locomotive trucks have been tested and three series of component tests have been conducted.

Testing Overview



Truck Test Articles

Truck test articles were chosen by the FRA to represent a cross section of trucks commonly used by U.S. railroads. Six three-axle designs were tested. The HTC trucks built by the Electromotive Division (EMD) of General Motors employ rubber pad compression springs in the secondary suspension. HTC is an acronym for High Traction Configuration. The Flexicoil is an older EMD design employing helical springs in the secondary suspension. E8 is an old and very popular EMD design using a swing-hanger secondary suspension with transverse leaf springs. The U30 and E60 trucks are basically the same General Electric truck, with the U30 used for freight applications and the E60 used for all-electric Amtrak service. Both the U30 and E60 trucks employ rubber pad compression springs in the secondary suspension.

Two two-axle truck designs were also tested. The first design tested was the standard EMD GPSS truck that has a swing-hanger secondary suspension with rubber pad compression springs. The second was a modified GPSS design in which the rubber pad compression springs had been replaced by inclined rubber pad springs to give a softer suspension.

Truck Test Articles

Truck Designation	Manufacturer	Secondary Suspension
3-Axle		
HTC (Hard Rubber)	EMD	Rubber Pads in Compression
HTC (Soft Rubber)	EMD	Modified (Soft) Rubber Pads in Compression
Flexicoil	EMD	Coil Springs
U30	GE	Rubber Pads in Compression
E60	GE	Rubber Pads in Compression
E8	EMD	Swing-Hanger: Leaf Springs
2-Axle		
GPSS	EMD	Swing-Hanger: Rubber Pads in Compression
GPSS (Amtrak Modified Rubber Pads)	EMD	Swing-Hanger: Inclined Rubber Pads

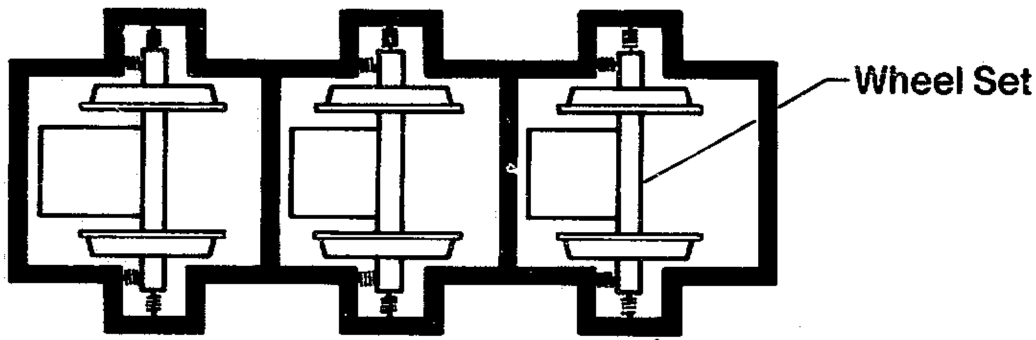
Suspension Idealization

A typical locomotive truck is composed of three major elements--frame, wheel set(s), and bolster--connected by mechanisms such as springs, dampers and bearings. A truck contains primary and secondary suspension systems.

This slide details the primary suspension system, which provides the connection between the wheel set(s) and the frame. The main feature of this suspension system is a system of helical compression springs located at the wheel bearing housing (side view) to provide vertical isolation between the frame and wheel set(s). Lateral and longitudinal isolation is a function of wheel bearing and pedestal liner characteristics. Damping is provided through the addition of external vertical dampers and the friction between the frame pedestal and wheel bearing journal box.

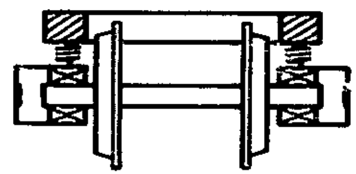
Suspension Idealization

- Primary Suspension: Frame/Wheel Set Connection



Top View

Side View



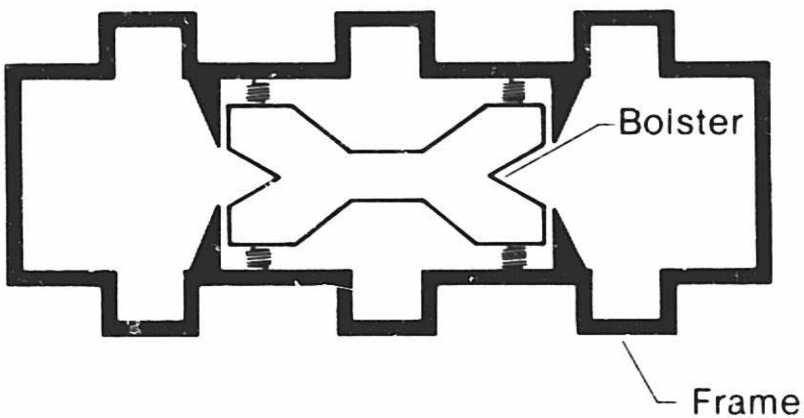
Front View

Suspension Idealization (cont)

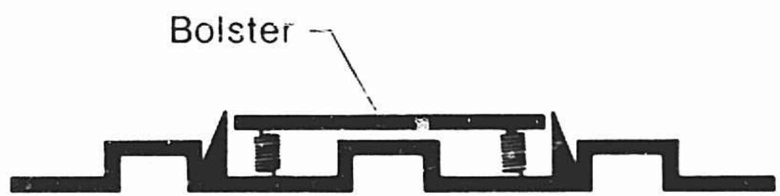
The secondary suspension isolates the bolster from the truck frame. Two basic design concepts are employed--the standard design (shown in this slide) and the swing-hanger design. The standard design may include rubber pad springs, helical steel springs or leaf springs. Traction stops limit the relative bolster/frame longitudinal motion to transfer traction and braking forces. Damping is provided by friction between the bolster and traction stops. In some designs external lateral dampers are added between the bolster and frame.

Suspension Idealization (cont)

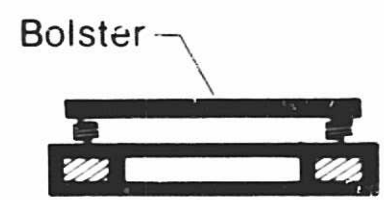
- Secondary Suspension: Bolster/Frame Connection



Top View



Side View



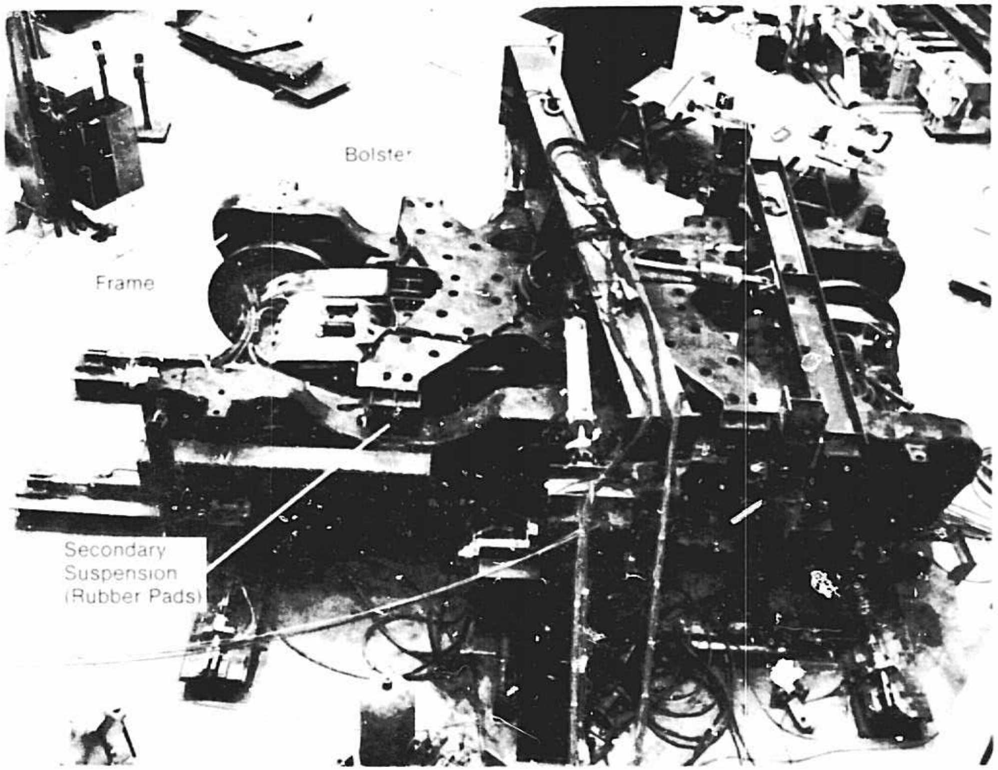
Front View

Standard Design

Standard Truck Design

This slide is a photograph of a standard three-axle truck design. Shown is a GE U30C truck installed in Martin Marietta's truck test fixture. Arrows denote the truck frame, bolster and secondary suspension rubber pad springs.

Standard Truck Design (3-Axle, U30C)

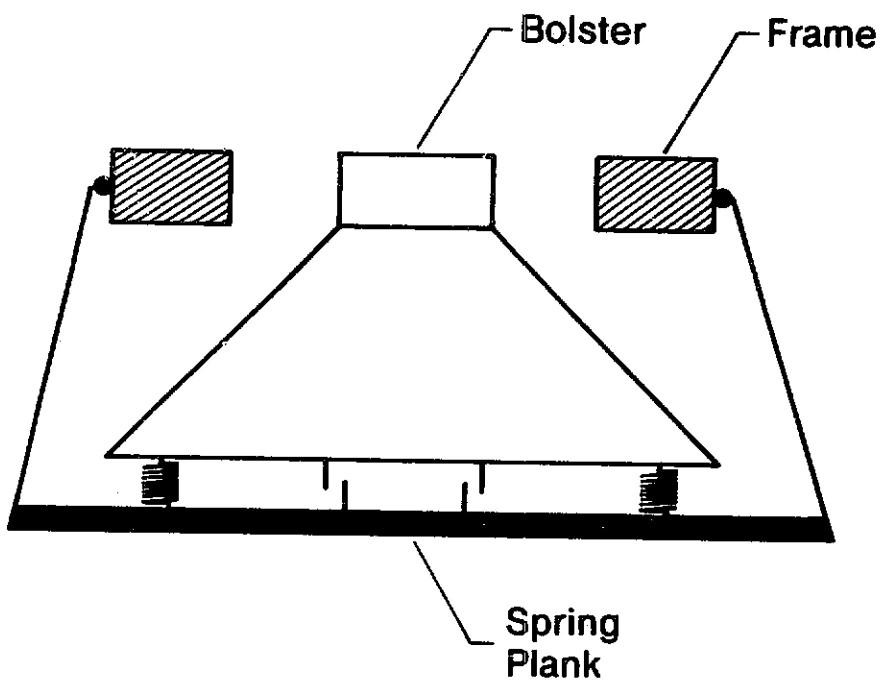


Suspension Idealization (concl)

This slide shows a sketch of the swing-hanger secondary suspension design concept. The bolster is connected to the frame through a pendulum support arrangement resulting in a soft secondary lateral suspension. Various types of springs provide the vertical connection between the bolster and spring plank. In this design, damping is again provided primarily by friction between the bolster and frame at the longitudinal traction stops.

Suspension Idealization (concl)

- Secondary Suspension: Bolster/Frame Connection



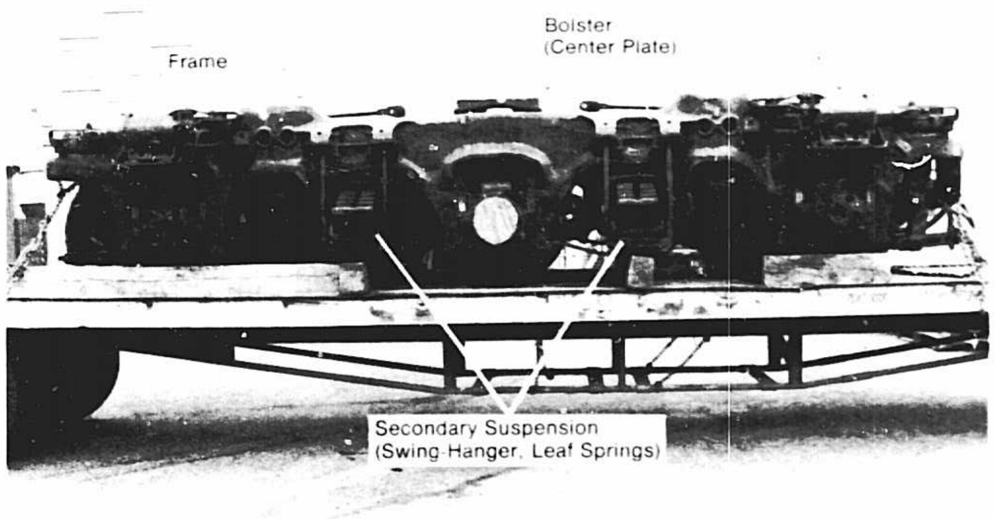
Front View

Swing-Hanger Design

Swing-Hanger Truck Design

Shown is a photograph of the EMD E8 three-axle truck. The dual swing-hanger configuration can be clearly identified. Transverse leaf springs provide the secondary vertical suspension.

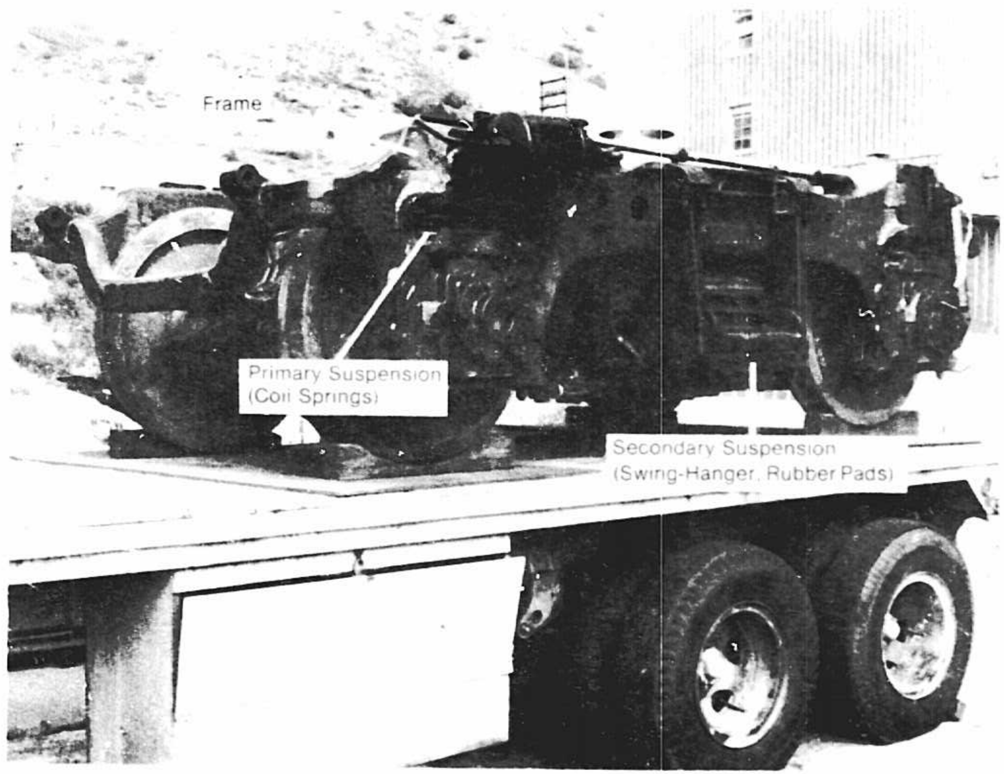
Swing-Hanger Truck Design (3-Axle, E8)



Swing-Hanger Truck Design (concl)

This slide shows a photograph of another swing-hanger design, in this case a two-axle EMD GPSS truck. This truck employs rubber pad compression springs in the secondary vertical suspension. This photograph also clearly shows the primary suspension coil springs.

Swing-Hanger Truck Design (2-Axle, GPSS)



Suspension Degrees of Freedom

The various parameters used to characterize a truck mathematically may be classified as acceleration-, velocity- or displacement-sensitive. The acceleration-sensitive characteristics are related to the truck's mass properties. Velocity-sensitive characteristics include the damping due to rubber pad springs and auxiliary devices such as shock absorbers. Displacement-sensitive characteristics include the stiffness properties of the truck's suspension system.

The test approach was formulated to measure the displacement-sensitive characteristics and friction. Although friction is sensitive to the direction of velocity, it is nearly independent of the magnitude of velocity. Mass properties and damping descriptors were calculated or obtained experimentally from element tests.

The test conditions were chosen to measure, either directly or indirectly, the load deflection characteristics representative of the degrees of freedom that might be used in a truck analytical model.

Suspension Degrees of Freedom

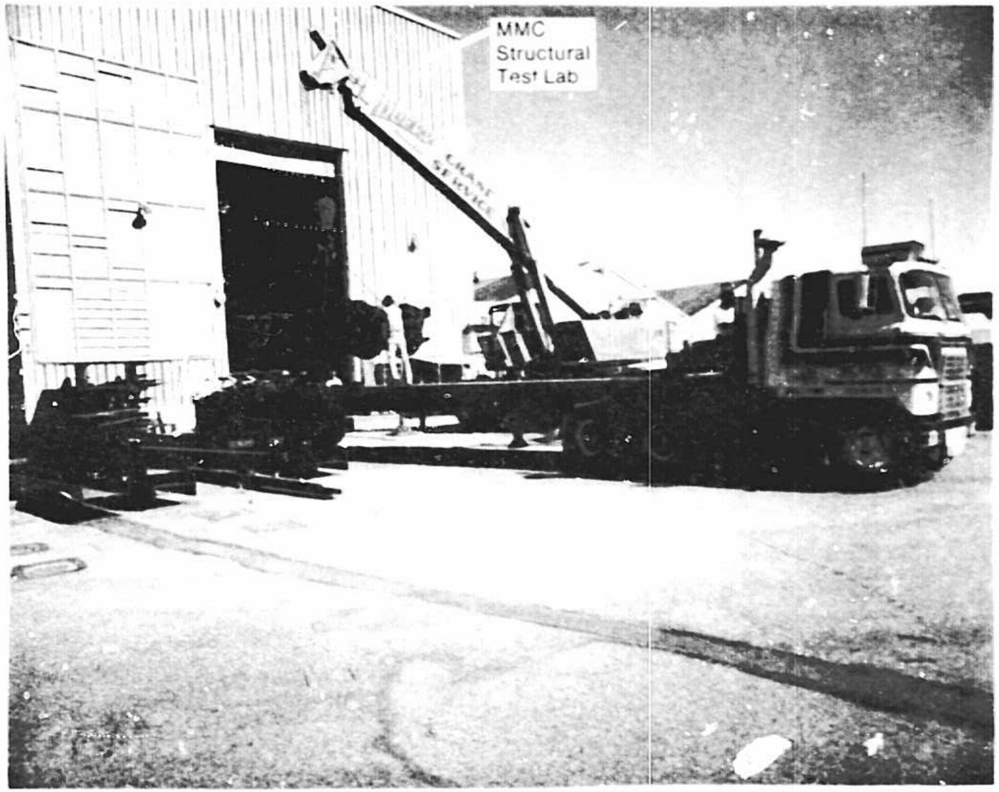
- Test Conditions Designed to Provide Suspension System Information Related to Truck Degrees of Freedom:

  Bolster Vertical/Roll
  Frame Vertical/Roll
  Bolster Lateral
  Frame Lateral/Yaw
  Wheel Set Lateral
  Wheel Set Yaw
  Car Body/Bolster Yaw (Yaw Friction)

Truck Test Facility

Martin Marietta's Locomotive Truck Test Facility is located in the Structural Test Laboratory at the Waterton facility in Denver, Colorado. Truck test articles were shipped to Denver via rail or ground transportation. The slide shows preparations to ship the EMD GPSS truck after test completion.

Preparing GPSS Truck for Shipment

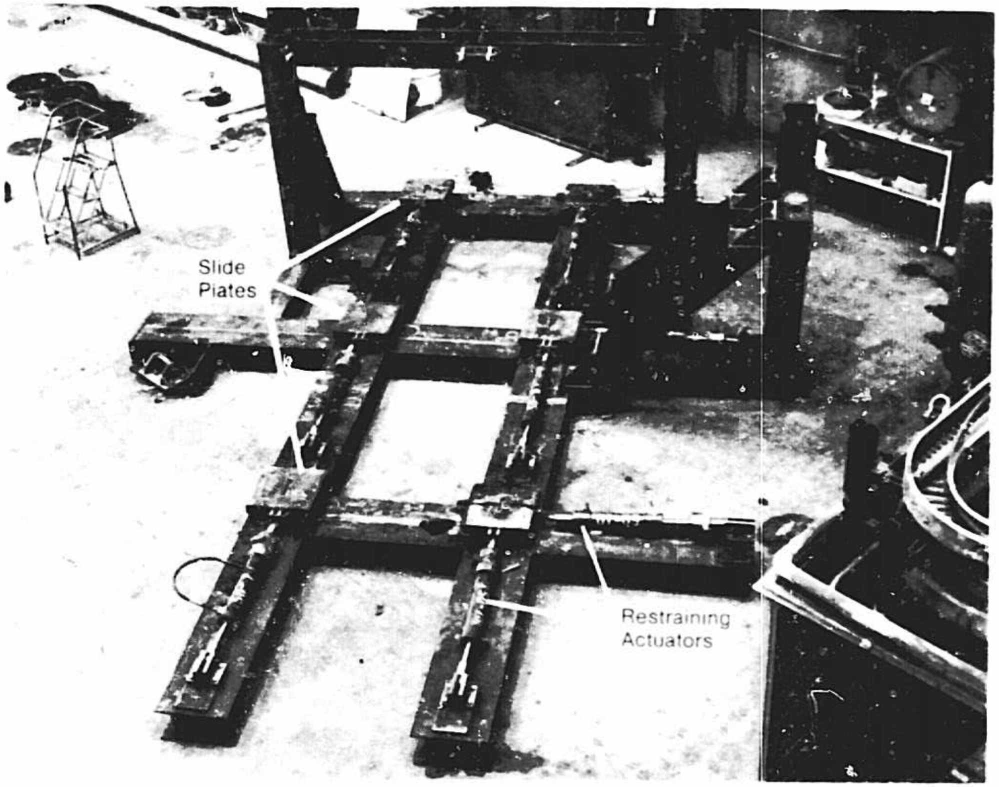


Locomotive Truck Test Fixture

This test fixture was designed by Martin Marietta and fabricated by the Transportation Test Center in Pueblo, Colorado. Anticipating a limited number of truck tests, a simple design was proposed. The design proved to be more than adequate for both the three- and two-axle trucks tested. The slide shows a photograph of the basic fixture configured for a three-axle truck.

The truck wheels were mounted on slide plates with hydraulic actuators used to react wheel loads. To provide proper boundary conditions, low-friction slide plates were required. Instead of using a hydraulic oil film bearing, a simple design evolved. Both the slide plates and fixture base have opposing machined surfaces. Low-friction teflon tape on one surface and polyolefin grease on the other produced a measured friction coefficient of 0.063 to 0.089.

Locomotive Truck Test Fixture

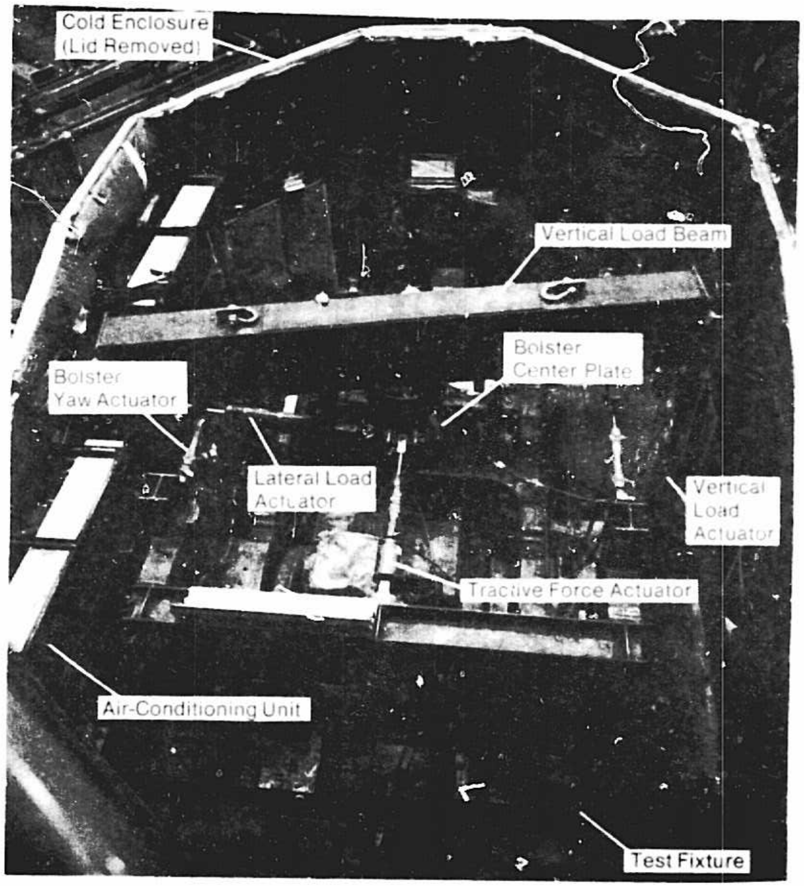


Martin Marietta Truck Test Facility

The slide shows a photograph of the Martin Marietta Truck Test Facility with the two-axle GPSS truck installed. The truck test fixture is housed in an insulated cold enclosure to allow testing at both ambient (approximately 70°F) and cold (approximately 0°F) temperatures. Trucks with rubber pad suspension elements were tested at cold temperatures to evaluate the stiffness changes with temperature.

A vertical load beam loaded the bolster to simulate the static car body weight. Other loads imposed on the bolster included lateral and tractive effort/braking loads (depending on the test condition). The yaw actuators shown were employed in the yaw friction tests that measured friction between the car body and bolster center plate for both dry and lubricated interfaces.

MMC Test Facility—GPSS Truck Installed



Test Instrumentation

Strain gage load cells in series with the hydraulic actuators were used to measure test loads. Both potentiometer and linear variable differential transformer (LVDT) deflection transducers were used to measure relative deflection within the truck's suspension system. System accuracy was measured at approximately 2% of full-scale calibration.

Test Instrumentation

Load Application: Hydraulic Actuators/Load Cells

50 to 200 klb
$\leq$ 3 Hz

Deflection Measurement: LVDT & Potentiometer Transducers

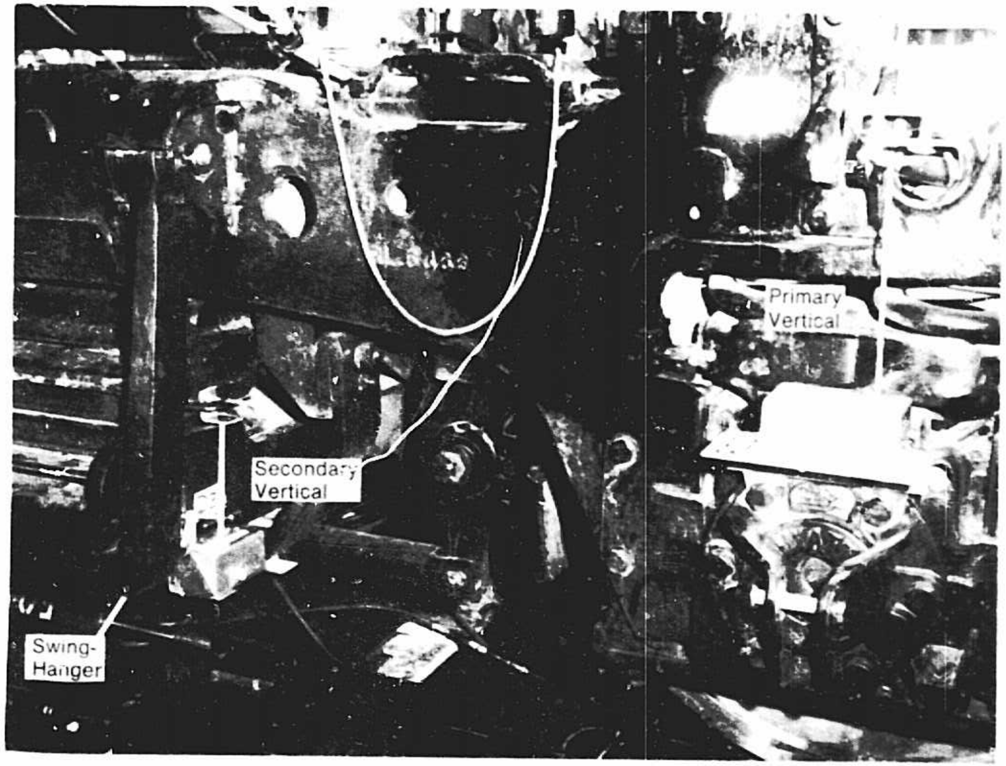
$\geq$ 4.0 in. Full Scale
$\pm$ 1% Full-Scale
Accuracy

Total System Accuracy $\pm$ 2% of Full-Scale Calibration.

Typical Truck Instrumentation

This photograph shows typical instrumentation for the GPSS truck. Shown are potentiometer deflection transducers configured to measure secondary and primary vertical suspension characteristics. These potentiometer transducers can measure deflections up to 4 inches full scale.

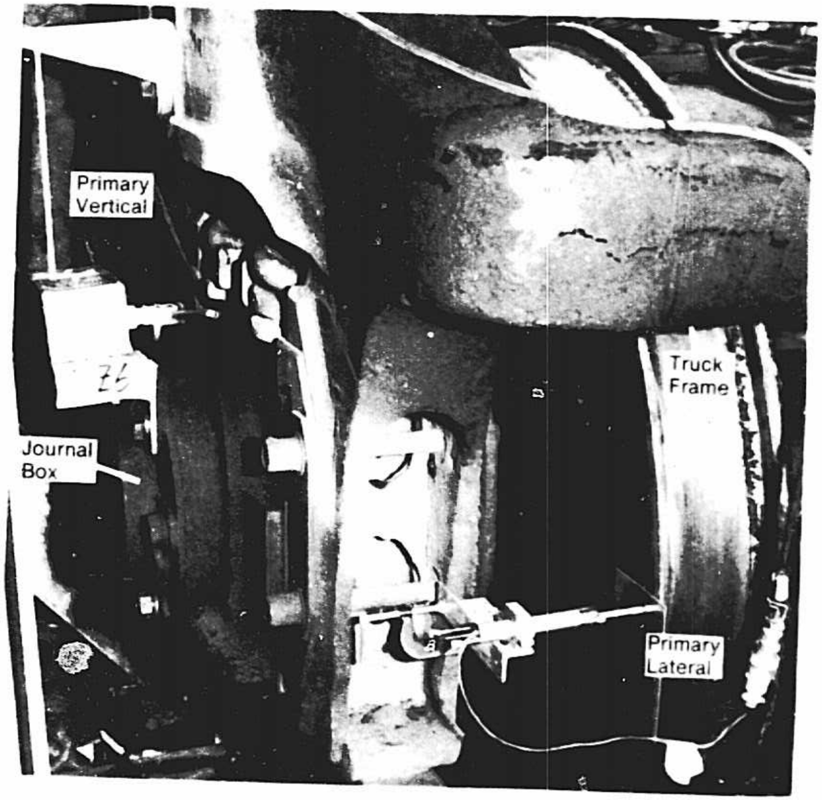
Typical Instrumentation, GPSS Truck



Typical Truck Instrumentation (concl)

This photograph shows the primary lateral measurement in addition to the primary vertical measurement. An LVDT transducer was used in the lateral application because of the smaller expected deflections.

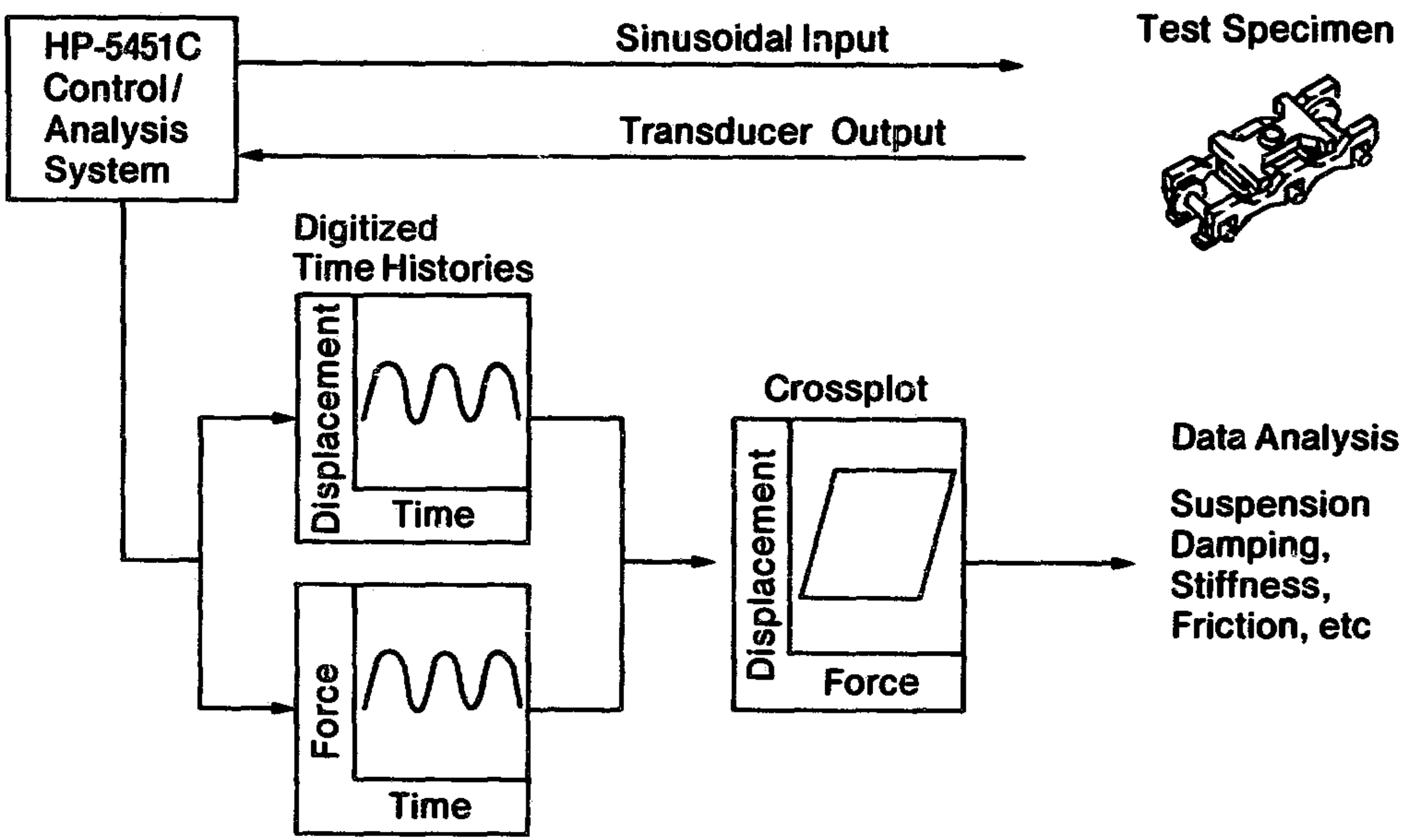
Typical Instrumentation, GPSS Truck



Data Reduction

The method of acquiring and reducing test data has evolved over the years. This slide delineates our test methodology that employs a computer-based HP-5451C control/analysis system. Using this system we are able to simultaneously output excitation signals to the test specimen and acquire transducer outputs. The transducer outputs (load and deflection) are digitized in real time and stored on a magnetic storage disk. The computer then operates on the digital data converting them to engineering units and crossplotting force and displacement. These crossplots (or hysteresis plots) are then analyzed to determine suspension damping, stiffness, and friction characteristics.

Near-Real-Time Data Reduction



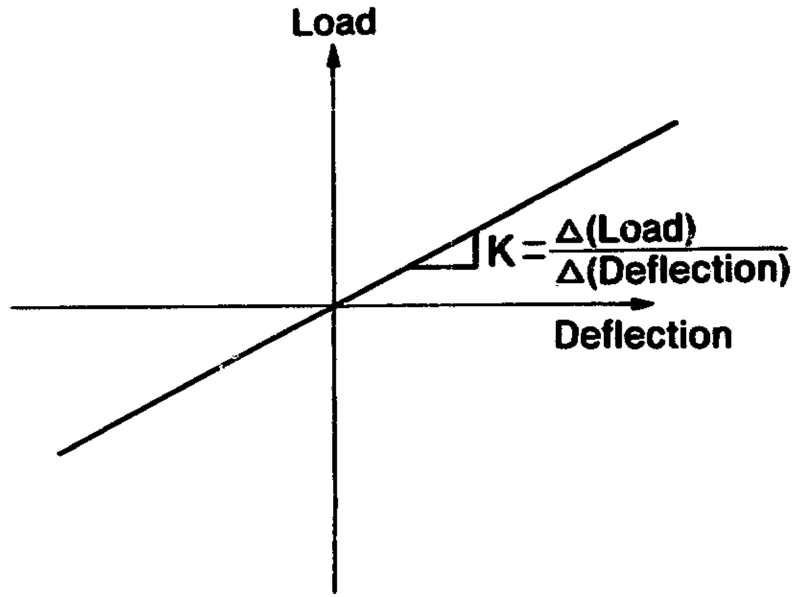
Data Interpretation

The following six slides show the various types of suspension characteristics measured during testing and discuss interpretation of the data.

Linear Stiffness - The linear load deflection curve shown is typical of linear springs such as the coil springs found in a truck primary suspension system. The spring constant or stiffness of the spring is expressed as the ratio of delta load over delta deflection and is the slope of the curve, K.

Data Interpretation

- Stiffness Characteristics
  Linear Stiffness

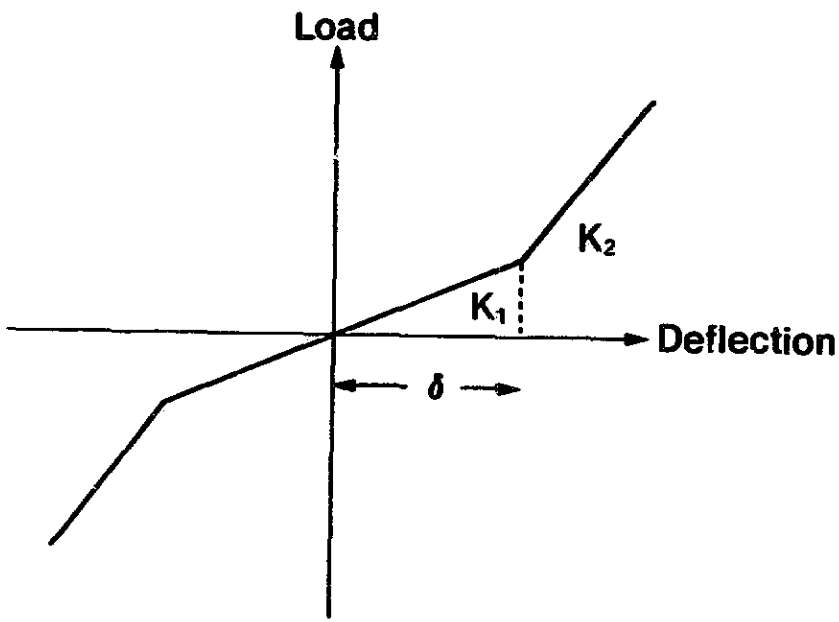


Typical of Primary Vertical Suspension (e.g., Coil Springs)

Bilinear Stiffness - The bilinear stiffness characteristics shown are typical of a linear suspension element that has deflection limit stops. An example is a lateral suspension element such as a rubber pad spring in shear with a lateral travel stop after a delta deflection. The spring constant K_2 is usually much greater than K_1.

Data Interpretation (cont)

- Stiffness Characteristics
  Bilinear Stiffness



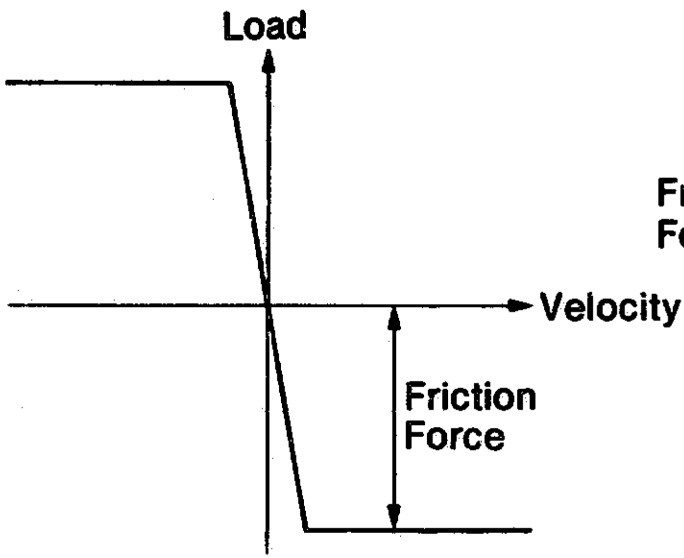
Typical of Secondary Lateral Suspension
(e.g., Rubber Pads with Lateral Limiter)

Friction - Most locomotive truck designs rely heavily on friction to provide damping. Although the sense of the friction force is determined by the direction of the velocity vector (friction force retards motion), the magnitude of the friction force is nearly independent of the magnitude of the valocity vector. This slide shows the hysteresis curve for pure friction. The area within the hysteresis loop is a measure of the energy dissipated per cycle of motion.

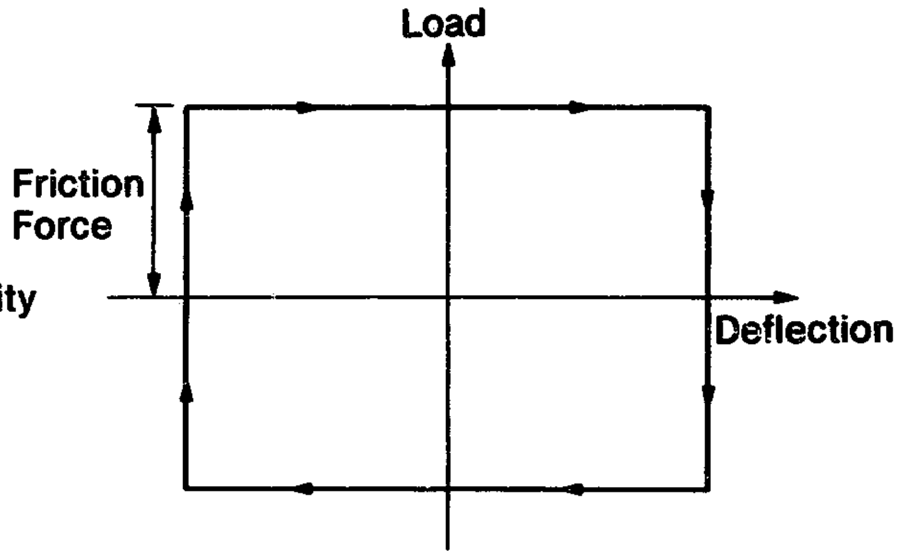
Data Interpretation (cont)

- Friction

Sense Determined by Velocity Vector



Pure Friction Plotted versus Displacement

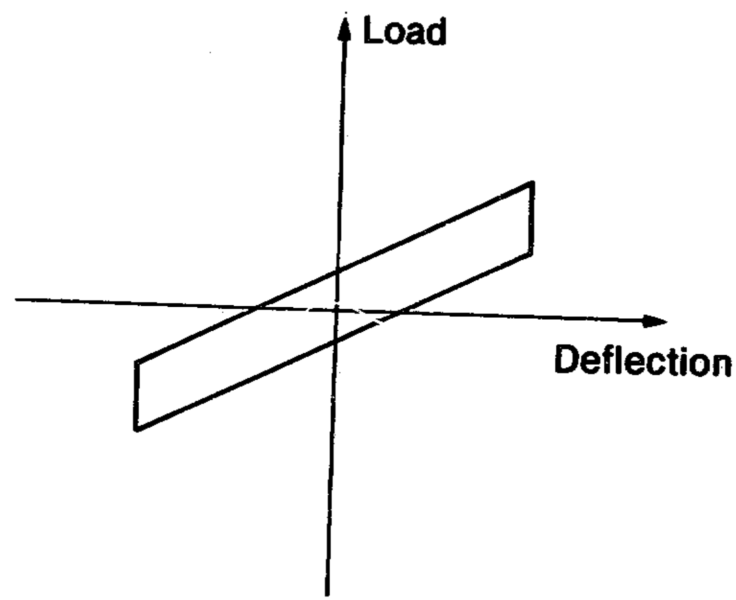


Linear Stiffness plus Friction - Most suspension elements can be characterized by a combination of stiffness and friction. The slide shows the hysteresis typical of a linear spring combined with friction.

Data Interpretation (cont)

- Combined Suspension Characteristic - Friction + Stiffness
  Friction-Induced Hysteresis

Linear Stiffness
plus Friction

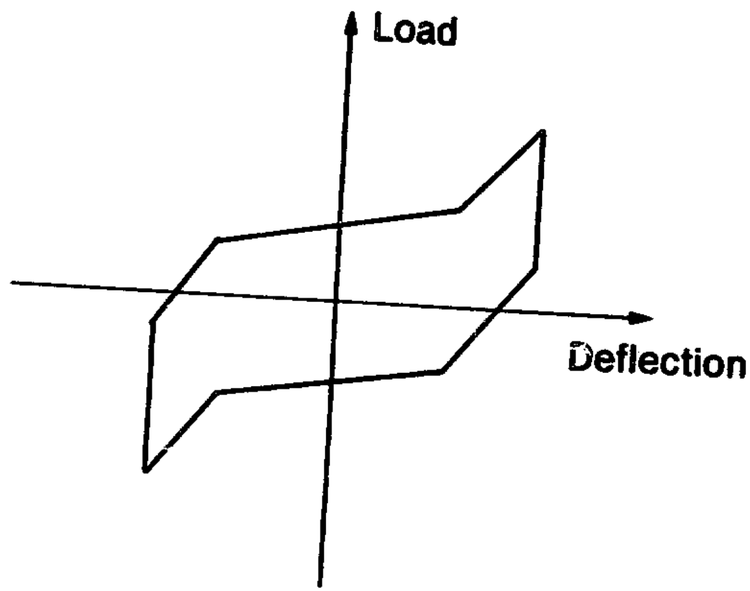


Bilinear Stiffness plus Friction - This slide shows the hysteresis characteristic of bilinear stiffness combined with friction.

Data Interpretation (cont)

- Combined Suspension Characteristic - Friction + Stiffness
  Friction-Induced Hysteresis

Bilinear Stiffness
plus Friction

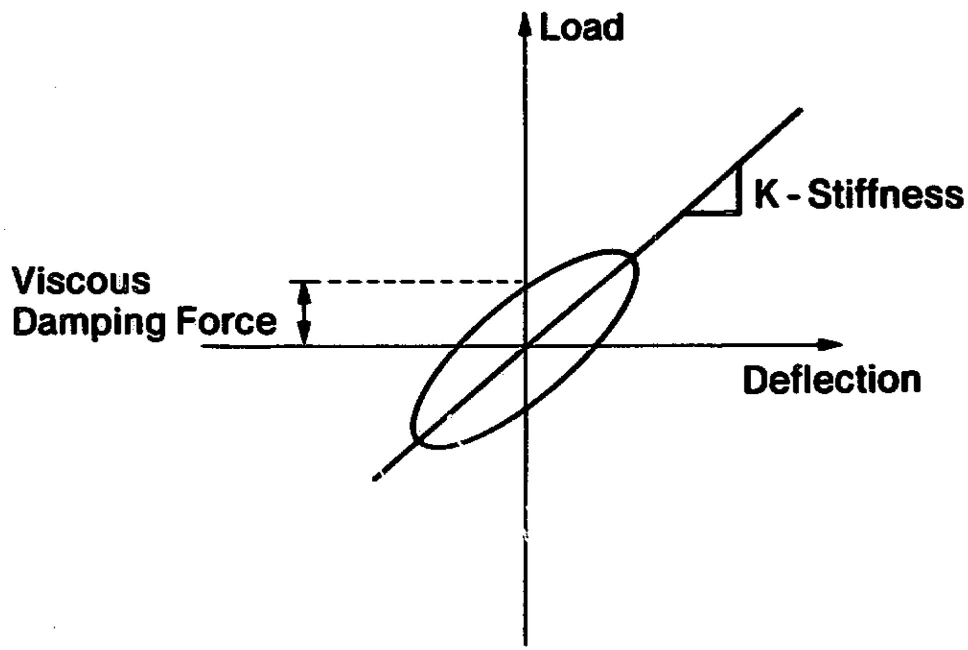


Viscous Damping - In addition to friction, a truck has other damping sources. Viscous damping is characteristic of rubber pad suspension springs and external hydraulic shock absorbers. This slide shows the hysteresis characteristic of a linear spring combined with viscous damping.

Data Interpretation (concl)

- Viscous Damping Combined with Linear Stiffness

Hysteresis Due to Viscous Damping



Approximation of Rubber Pad Springs

Truck Suspension Comparison - Vertical

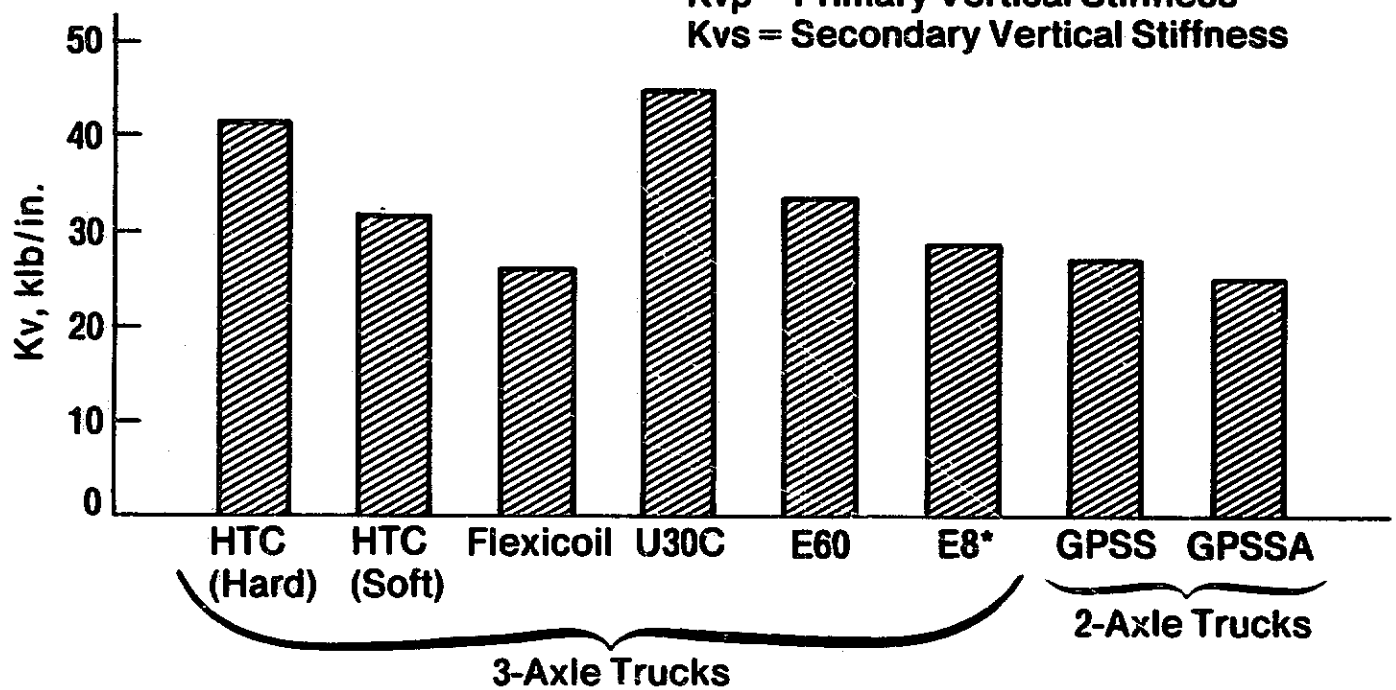
This slide shows the vertical stiffness of the eight trucks tested under this contract. Shown is the equivalent vertical stiffness of the primary and secondary suspension systems in series. Many of these trucks are available with a range of suspension stiffnesses to fit the service application. The values shown are representative and only reflect the trucks tested.

Truck Suspension Comparison

- Vertical

$$Kv = \frac{Kvp \times Kvs}{Kvp + Kvs} \text{ (Equivalent)}$$

Kvp = Primary Vertical Stiffness
Kvs = Secondary Vertical Stiffness



Temperature ≈ 70°F,
Excitation Frequency ≈ 0.25 Hz

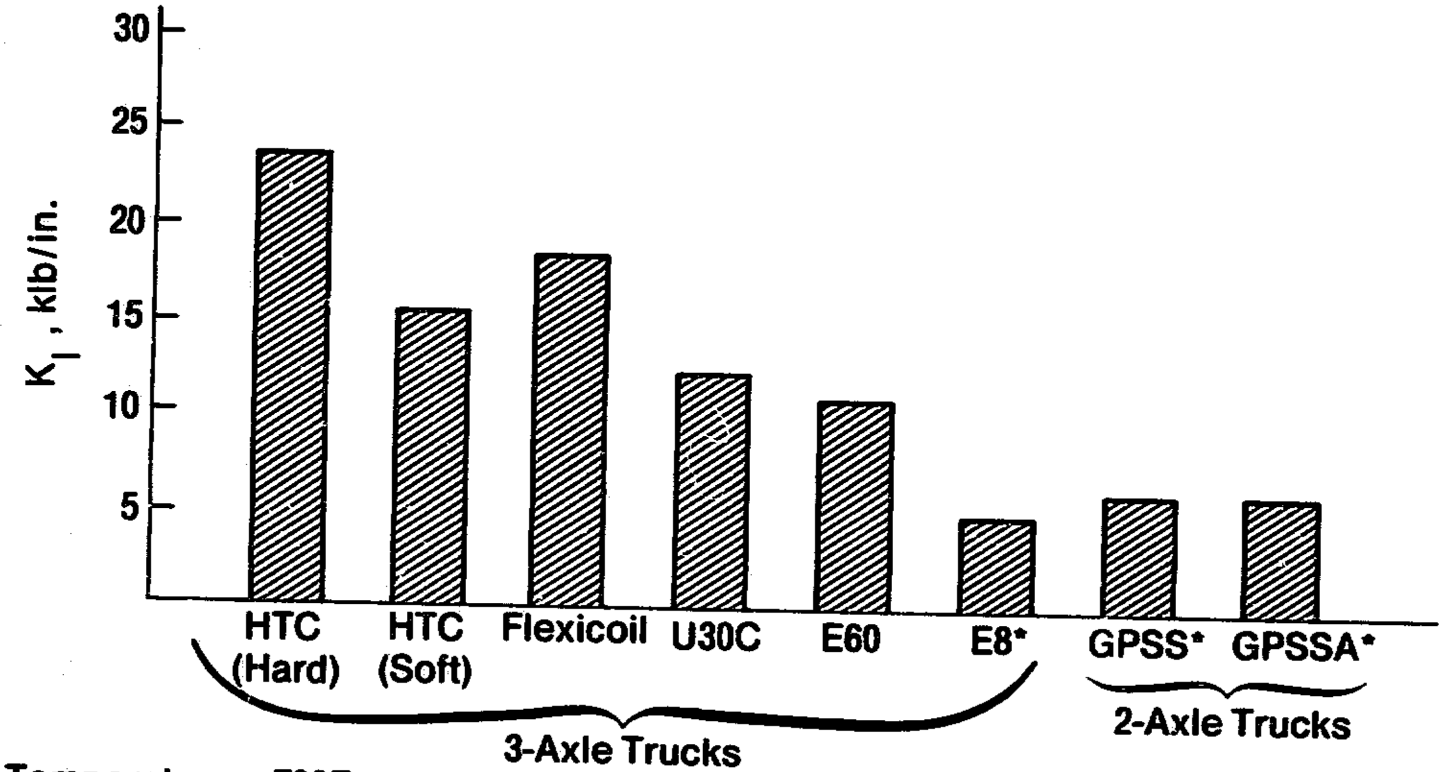
*Load equalization.

Truck Suspension Comparison - Lateral

This slide compares the secondary lateral suspension stiffness of the eight trucks tested. Note that the swing-hanger (pendulum) lateral suspension used in the E8, GPSS, and GPSSA trucks significantly reduces lateral stiffness.

Truck Suspension Comparison (concl)

- Lateral (Secondary)



Temperature ≈ 70°F,
Excitation Frequency ≈ 0.25 Hz

*Swing-hanger suspension.

Component Test Programs

In addition to the truck tests, three component test programs were conducted under the contract. The objective of these test programs was to investigate in more depth the characteristics of key suspension components. The component test programs conducted are delineated on the slide.

Component Test Programs

• Rubber Suspension Pads:	Determine Stiffness & Damping Characteristics [HTC (Hard & Soft), E60]
• Hyatt Bearing Lateral Bumper:	Determine Stiffness of Lateral Thrust Bumper
• Shock Absorber-Friction Snubber:	Determine Energy Dissipation Characteristics [HTC (Delco P/N 22012514), U30 (Houdaille P/N 709702-11)]

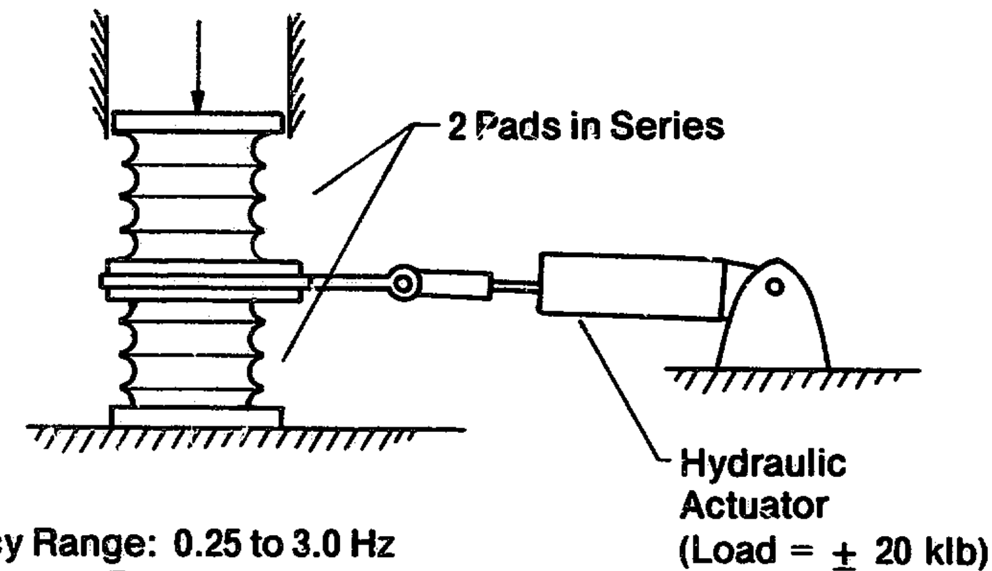
Rubber Pad Element Tests

The truck tests did not provide sufficient resolution to allow a complete understanding of elastomeric pad properties. Since the pad is a key element in determining truck behavior, a separate element test was performed to verify the pad characteristics.

A simple test fixture was constructed to allow measurement of rubber pad stiffness and damping properties as a function of pad temperature and frequency of excitation. The slide shows a sketch of the test set-up. Two pads were preloaded in series with approximately 1/8 the weight of a car body, and a hydraulic actuator was used to load the pads in shear. Load deflection characteristics were measured over a temperature range from -55 to 70°F and an excitation frequency range from 0.25 to 3.0 Hz.

Rubber Pad Element Tests

- Secondary Suspension Pads Tested: HTC (Hard & Soft), E60

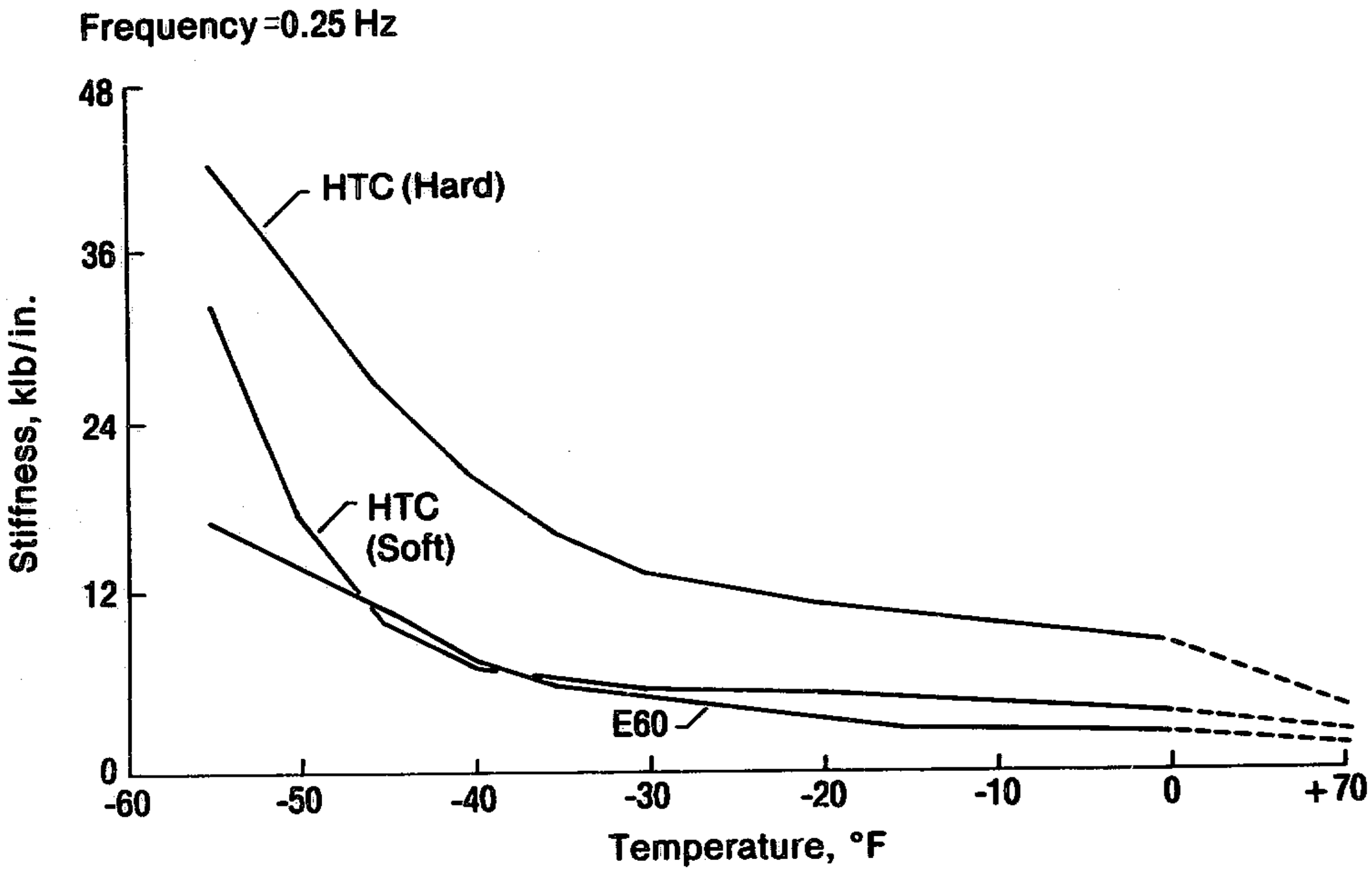


Excitation Frequency Range: 0.25 to 3.0 Hz
Temperature: -55 to +70°F

Rubber Pad Stiffness vs Temperature

This slide shows the variation in stiffness as the pad temperature is lowered. The frequency of excitation was 0.25 Hz.

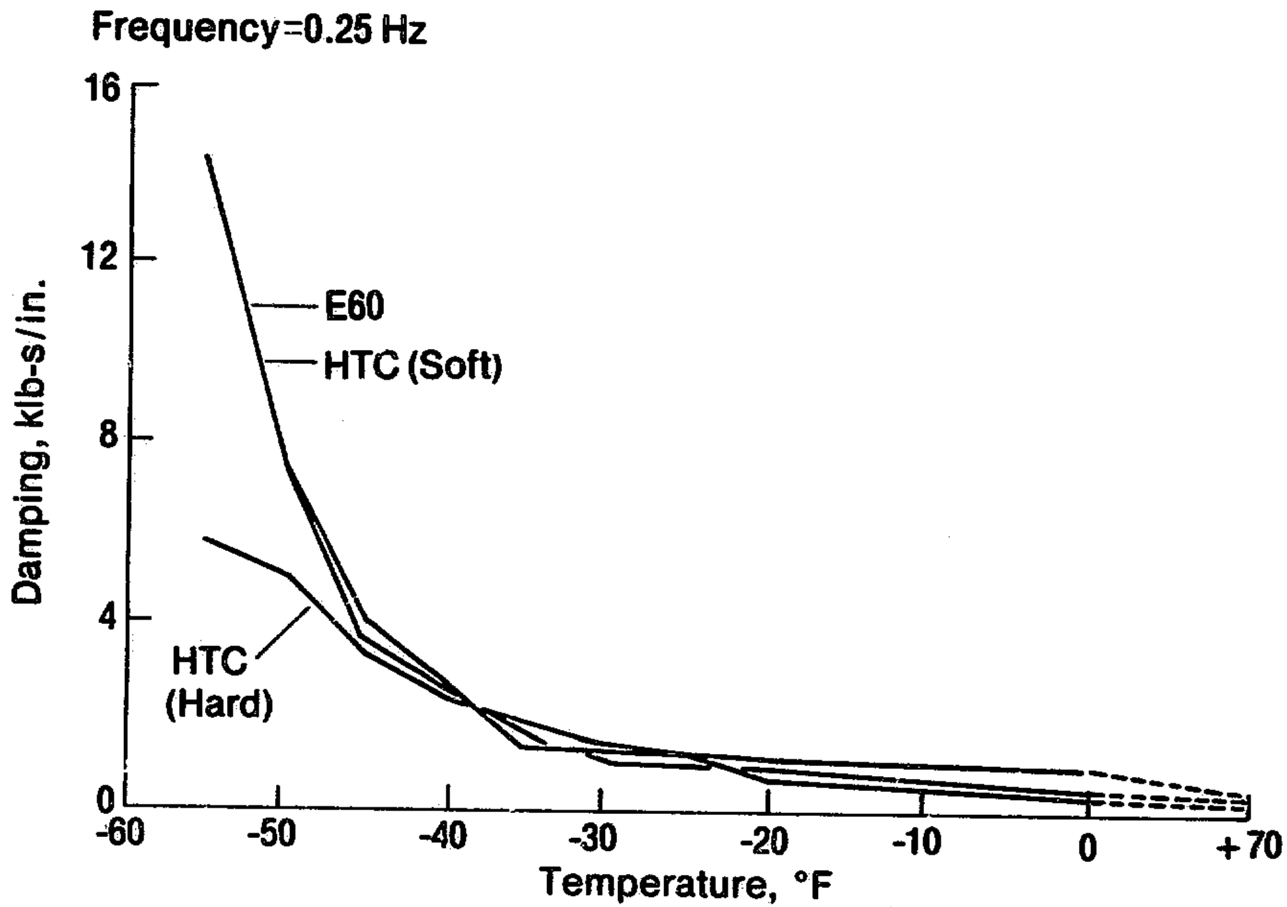
Rubber Pad Stiffness versus Temperature



Rubber Pad Damping vs Temperature

This slide shows the increase in pad damping with a decrease in pad temperature. This trend is typical of polymer materials. In general rubber pad springs are not good dampers because they are functioning in the "rubbery region" as opposed to the "viscoelastic region." Polymer materials have a critical temperature called the glass transition temperature. At this temperature the material enters the "plastic region" and is more susceptible to fracture damage. The glass transition temperature occurs below the "viscoelastic region." For the pads tested, the viscoelastic region appears to be below -40°F. In operation the pads will be at a much higher temperature than this because of internal heat generation.

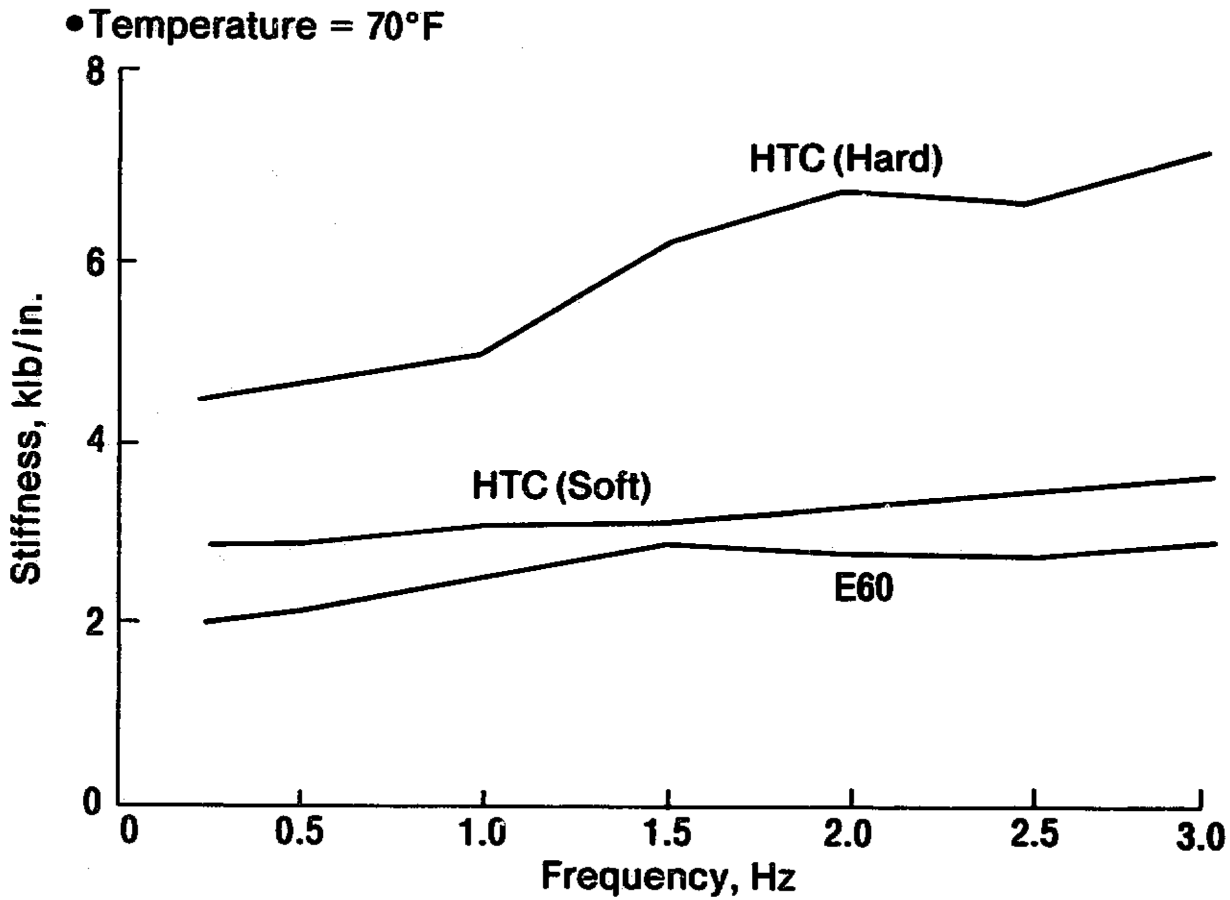
Rubber Pad Damping versus Temperature



Rubber Pad Stiffness vs Frequency

This slide shows the nonlinearity of pad stiffness as the excitation frequency is varied.

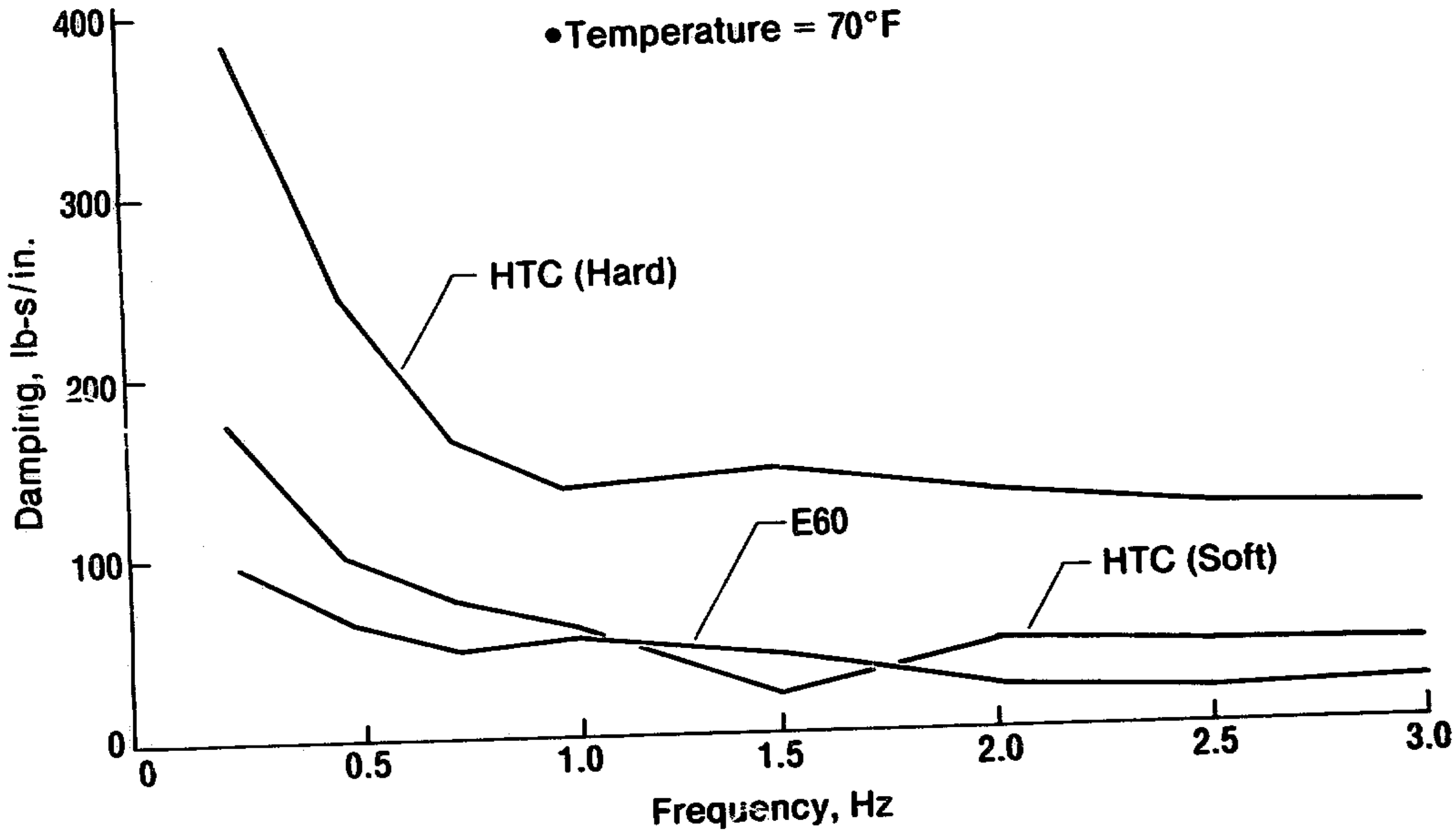
Rubber Pad Stiffness versus Frequency



Rubber Pad Damping vs Frequency

This slide shows the variation in damping coefficient as excitation frequency is varied. Rubber pad characteristics can be analytically modeled with a variety of spring-damper analogs. However, the Jet Propulsion Laboratory (JPL) has conducted some basic material testing for the FRA that promises to result in a rational mathematical formulation of rubber pad spring characteristics.

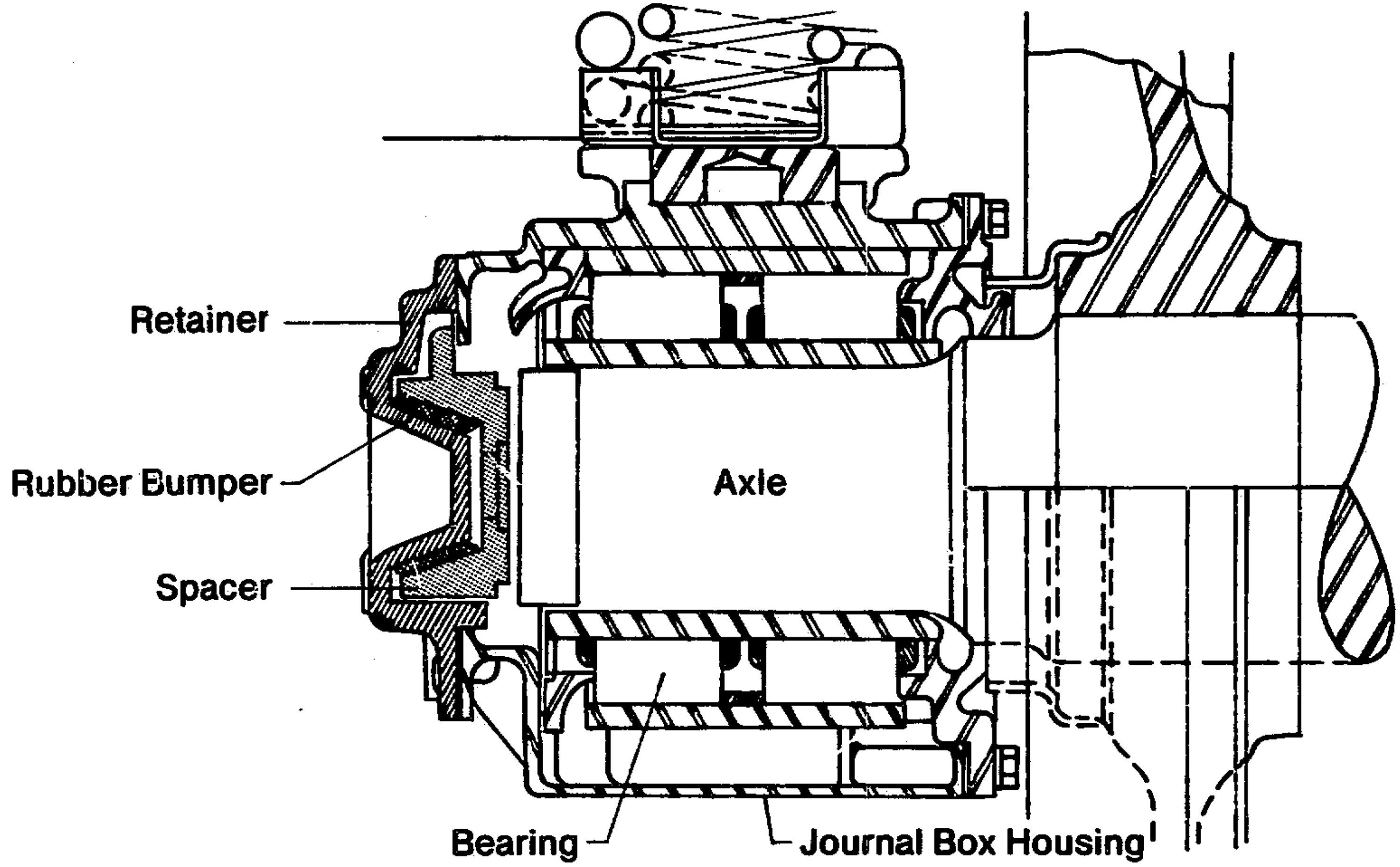
Rubber Pad Damping versus Frequency



Hyatt Bearing Element Test

Hyatt bearings, in contrast with tapered Timken bearings, do not carry lateral thrust loads (along the axle shaft) except through rolling friction. Once the free-play clearance is exceeded, a rubber bumper reacts the lateral load to the journal box. This slide shows details of the bearing construction and identifies the location of the rubber bumper. Because the friction resulting from the wheels rolling could not be simulated during testing, bumper stiffness could not be characterized. Consequently an element test was conducted to measure the bumper's properties.

Hyatt Bearing Details



Hyatt Bearing Bumper Components

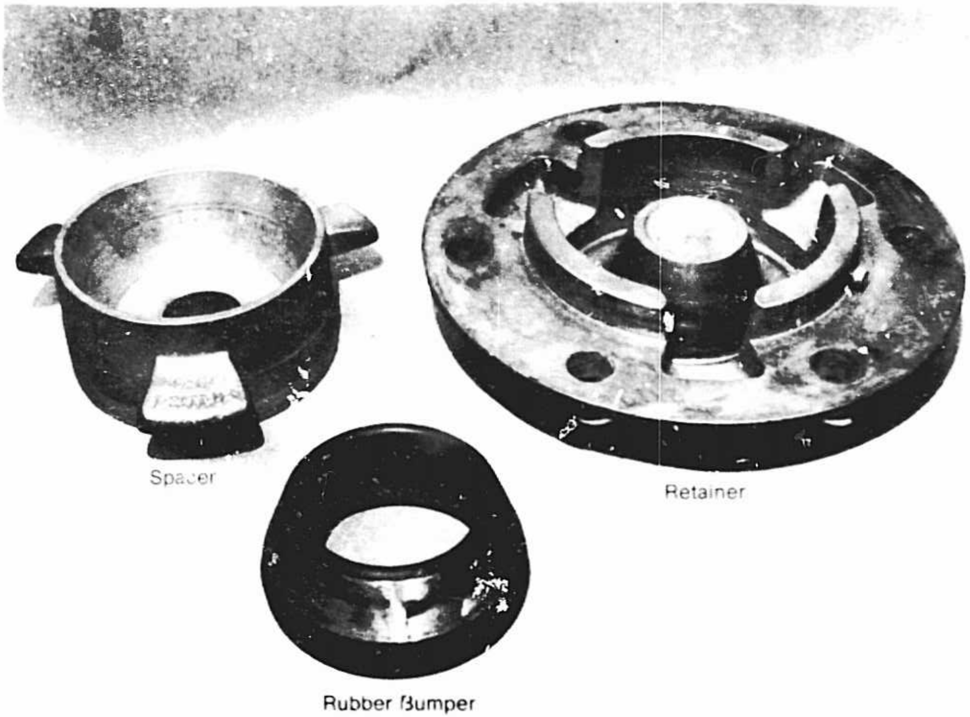
Testing was conducted on an MTS testing machine that plotted load versus deflection. During testing the bumper was configured with the spacer and retainer similar to its installed configuration in the bearing to provide realistic boundary conditions. The photograph shows the bumper with its spacer and retainer.

The resulting load deflection curve was fit with a polynominal expression relating load and bearing deflection

$$\text{Load} = 1.440 \times 10^4\, X - 1.495 \times 10^5\, X^3 + 1.704 \times 10^7\, X^5 - 3.077 \times 10^8\, X^7 + 1.751 \times 10^9\, X^9$$

where X = bumper deflection.

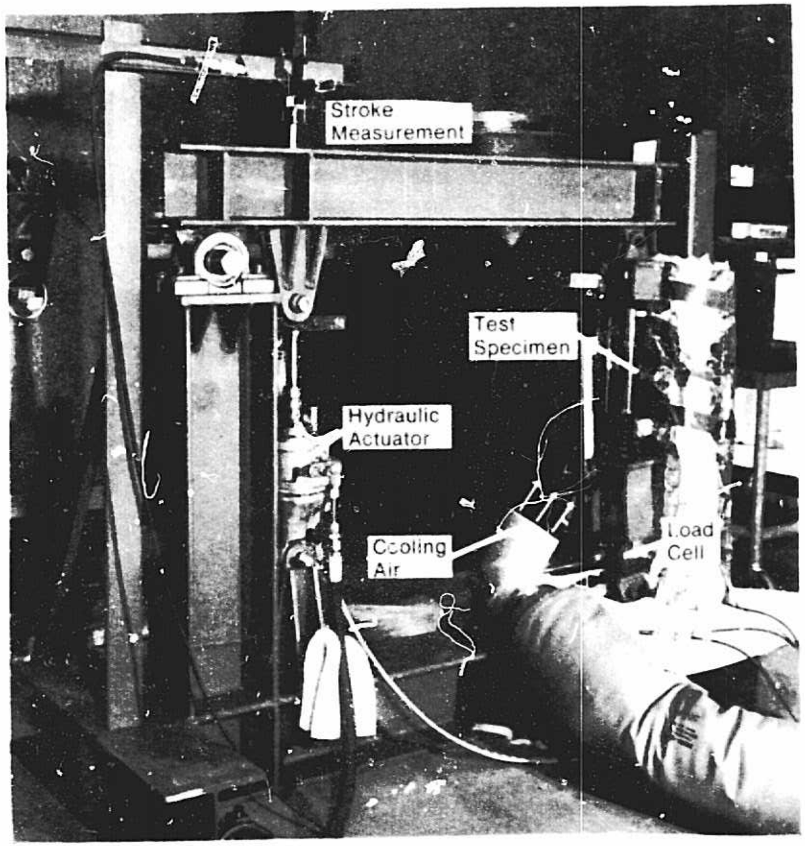
Hyatt Bearing Bumper Components



Shock Absorber-Friction Snubber Element Test

A component test program was conducted to evaluate the damping characteristics of two representative external damping devices--a Delco 22012514 hydraulic shock absorber commonly used on EMD HTC locomotive trucks, and a Houdaille 709702-11 friction snubber commonly used on GE U30 trucks. The slide shows a photograph of the test setup. An "oil derrick" fixture was fabricated to facilitate a range of stroke amplitudes. A hydraulic actuator was used to load the test specimen utilizing the fixture's mechanical advantage to magnify its limited stroke displacement. A strain gage load cell and two LVDT displacement transducers were used to measure the load deflection characteristics of the test specimens. A range of stroke velocities and displacements was obtained by varying excitation frequency and load. Specimens were tested over a temperature range from -50 to 165°F. Thermocouples mounted on the specimens were used to determine the test temperature. Liquid nitrogen-cooled air was used to control the specimens' temperature. The following slides summarize the measured data and compare them with the manufacurer's specifications.

Shock Absorber Test Fixture

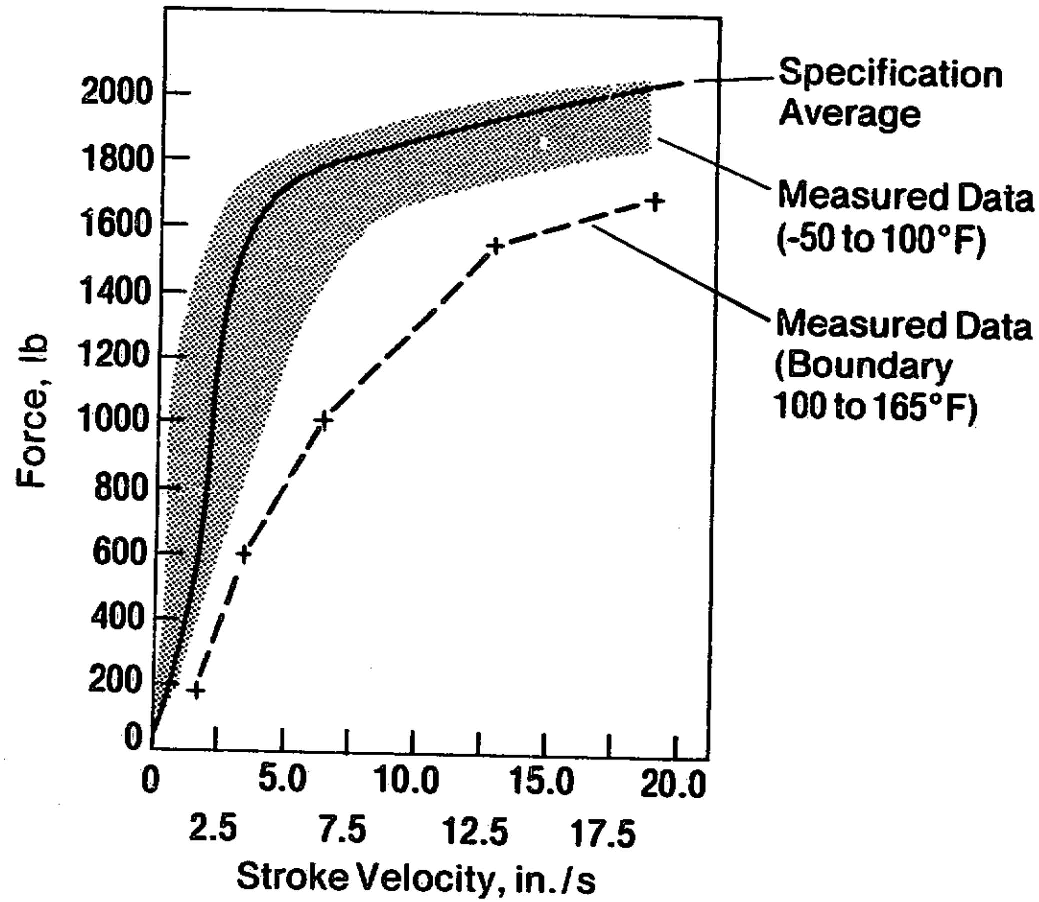


HTC Shock Absorber Characteristics

This slide is a plot of damping force versus stroke velocity showing a comparison between measured test data and the manufacturer's specification average for the Delco 22012514 hydraulic shock absorber. This shock absorber is commonly used on the EMD HTC truck. The shaded area encompasses the test data for the temperature range from -50 to 100°F. These data correlate well with the manufacturer's specification average. At higher temperatures, however, the shock absorber's performance falls off significantly. The boundary envelope of the measured data between 100 and 165°F is shown. No attempt has been made to determine the temperature of a shock under operational conditions. However, prolonged travel at low speeds over very rough track could result in higher than normal temperatures due to stroking of the shock.

HTC Shock Absorber Characteristics

- Delco P/N 22012514 Hydraulic Shock Absorber
- Stroke:
  0.25 to 2.0-in. DA
- Frequency:
  0.25 to 4.0 Hz



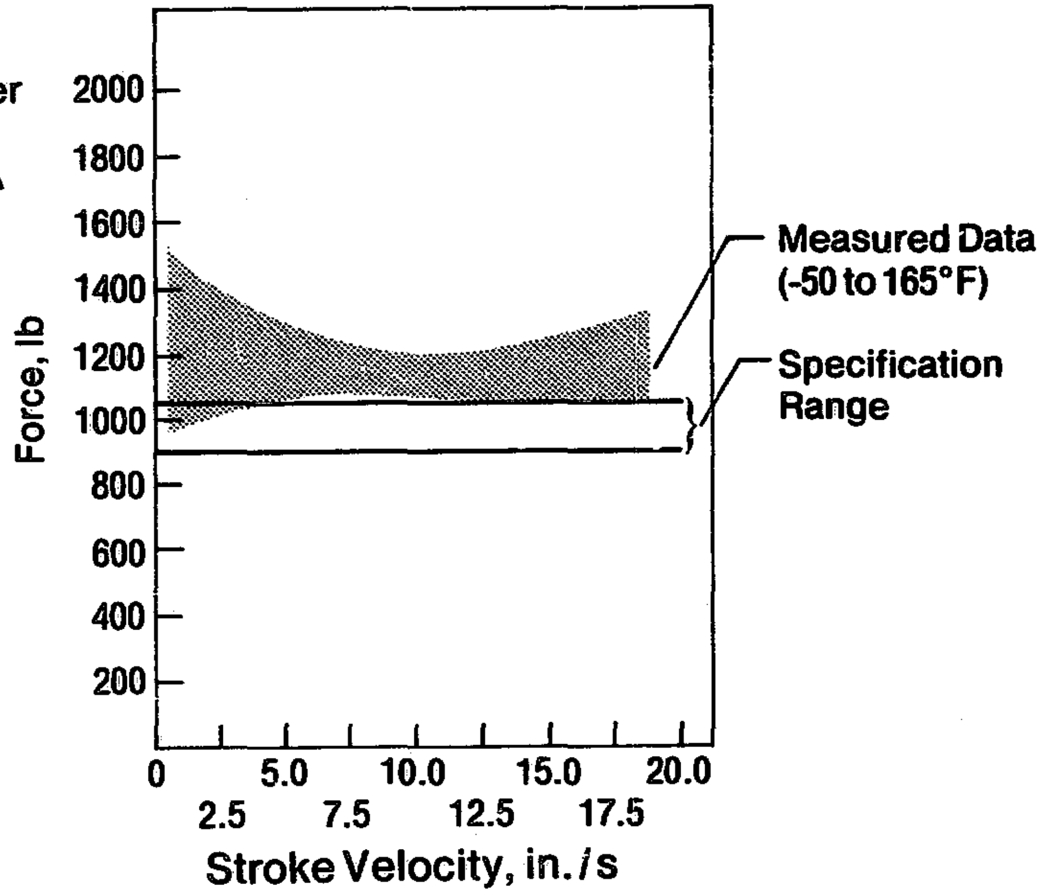
U30 Friction Snubber Characteristics

This slide presents data similar to the last, showing data for the Houdaille 709702-11 friction snubber. All measured data met or exceeded the manufacturer's specification range. This was true even for the high-temperature tests.

Comparing the characteristics of the friction snubber with those of the hydraulic shock absorber, we see the basic difference between a velocity-dependent damping device (the shock absorber) and a damping device based on friction (the friction snubber). The snubber provides a fairly constant damping force regardless of velocity.

U30 Friction Snubber Characteristics

- Houdaille
  P/N 709702-11
  Friction Snubber
- Stroke:
  0.5 to 2.0-in. DA
- Frequency:
  0.25 to 4.0 Hz



Locomotive Dynamic Characterization Test Report

In addition to individual reports published on each truck tested, a report (MCR-81-577) that summarizes all truck and component tests will be published. This report will summarize the test phase of the contract with sufficient data to allow analytical modeling of the trucks tested. Additional detail may be obtained from the individual truck test reports.

Locomotive Dynamic Characterization Test Report

- Total Locomotive Dynamic Test Program Summarized
  - Historical Background of the Project
  - Overview of Testing Accomplished
  - Discussion of Test Apparatus and Data Reduction
  - Physical Description of Trucks Tested and Summary of Test Data

Methodology Development

The second phase of this contract involved the development and demonstration of a methodology to evaluate locomotive operational safety. A computer code was developed to simulate the nonlinear response of a locomotive to rail geometry defects and calculate various measures of safety for evaluation. The code incorporates measured data from the test program.

Methodology Development

- <u>Objective:</u> Develop and Demonstrate a Methodology to Evaluate the Operational Safety of Locomotives

  - Incorporated Data from the Test Program (Available for First Time)

  - New Computer Code Developed to Assess Operational Safety: No Existing Code Directly Applicable

Methodology Tasks

This slide tabulates the individual methodology tasks. The initial efforts involved a review of existing track standards to bracket the range of expected track defects. The PTT and Chessie tests were reviewed to determine key locomotive parameters to analytically monitor during simulations. The track geometry defects used in the analyses were also based on the PTT defects.

The final methodology tasks included the development of a nonlinear locomotive simulation computer code and the use of this code to perform truck parameter sensitivity analyses. The model was also used to compare the response of three locomotive designs to a set of track geometry defects.

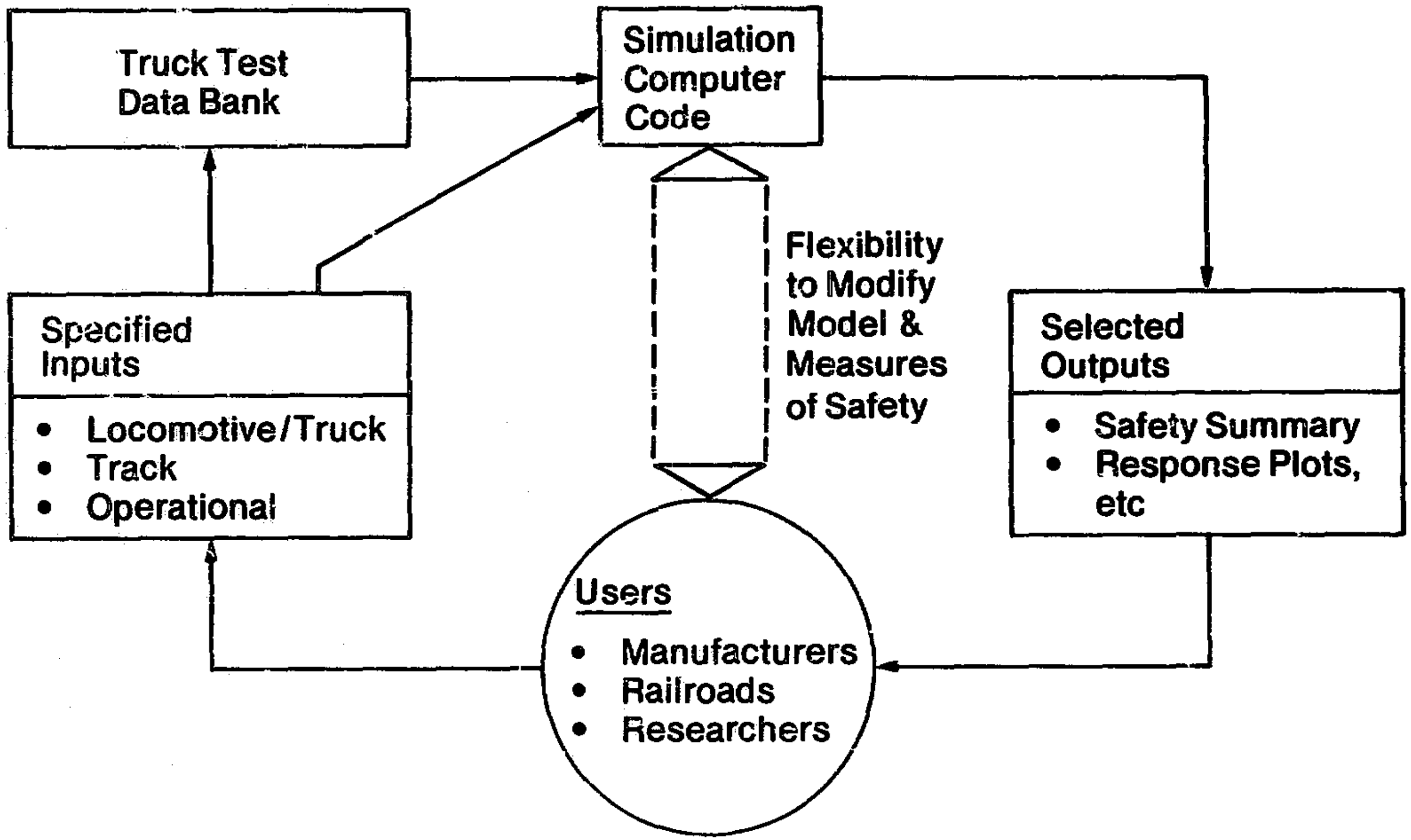
Methodology Tasks

- Review Track Standards to Determine Allowable Magnitudes of Track Geometry Defects
- Review Actual Track Records & Tests (PTT, Chessie) to Determine Realistic Geometry Defects for Analysis
- Develop a Detailed, Hardware-Oriented, Nonlinear Dynamic Model
- Compare Three Specific Designs [HTC (Soft), U30, E8]
- Perform Sensitivity Analysis to Determine Influence of Various Truck Parameters on Rail Safety

Modeling Approach

This slide presents the approach used in developing the nonlinear model. The computer code is user-oriented and provides the flexibility to modify the model and measures of safety if so desired. Input data are hardware-oriented and the units employed are those typically used in the railroad industry. The truck data obtained in the test program form the basis for the truck test data bank. The code is hosted on a CDC computer system in Fortran IV and operates in an interactive mode allowing a direct user/code interface.

Modeling Approach



Nonlinear Model

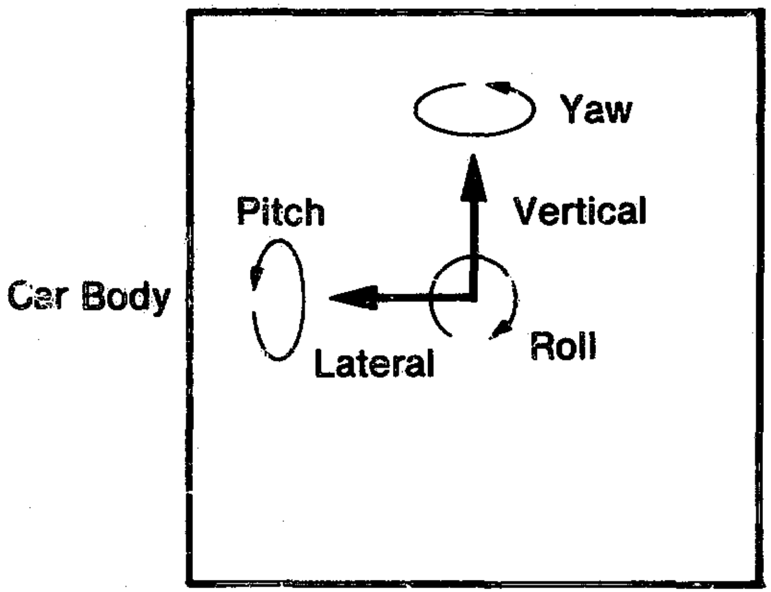
The formulation idealizes a locomotive using 15 degrees of freedom. This slide delineates the car body and truck degrees of freedom:

Car body	= 5 DOF
Leading truck	= 5 DOF
Trailing truck	= 5 DOF
	15 DOF Total.

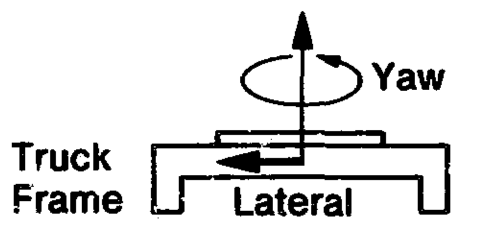
Nonlinear Model

Model has 15 degrees of Freedom:

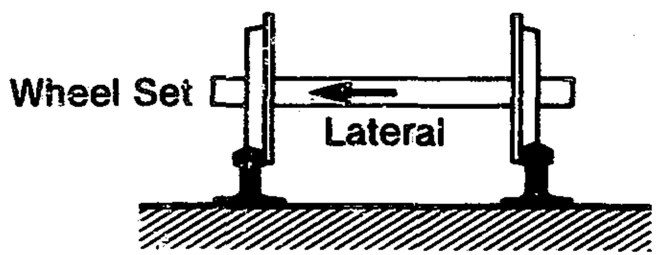
Car Body	=	5 DOF
Frame	=	2 DOF (ea)
Wheel Set	=	1 DOF (ea)



[Secondary Suspension]



[Primary Suspension]



Model Features

The model simulates the nonlinear time response of a locomotive to track geometry defects on curved or tangent track. Track geometry defects may be specified in terms of vertical, cross-level, or gage perturbations. Complex defects are constructed by superposition.

Wheel/rail interactions are modeled in detail. The model includes a nonlinear creep formulation and also simulates wheel flanging. All input data are hardware-oriented to facilitate use of the code.

Model Features

- Transient Track Geometry Inputs: Vertical
Lateral
Cross-Level
Gauge
- Simulates Tangent or Curved Track
- Detailed Wheel/Rail Interactions Modeled
- Hardware-Oriented Nonlinear Truck Suspension Representation: (Structured to Accept Test Data)
- Moderate Computer Cost ≈ $1 to $2/Simulated Second

Model Details

This slide lists the locomotive elements considered in the analytical formulation. The car body is assumed rigid. Each truck's primary and secondary suspension systems are modeled with the truck frame and wheel sets assumed rigid. In addition to wheel/rail interactions, the model allows specification of the constant coupler forces and wind loads.

Model Details

- Detailed Models of Nonlinear Suspension Elements and Interaction Forces
  - Secondary Suspension (Car Body/Truck Frame)
  - Primary Suspension (Truck Frame/Wheel Set)
  - Wheel Set/Rail Interaction
  - Coupler Forces
  - Wind Loads

Example Measures of Safety

The computer code automatically monitors the measures of safety tabulated on the slide--single-wheel L/V ratio, truck side L/V ratio, wheel set L/V ratio. The paper referenced delineates the concern thresholds for these measures of safety and they are presented on the slide. However, the user is free to interpret these parameters in any manner he chooses. The code may also be altered to monitor other measures of safety.

Example Measures of Safety

•Single Wheel L/V Ratio

- Indicator of Flange Climb Potential
- Concern Threshold: 0.9 to 1.0 for ≈ 50 milliseconds*

•Truck Side L/V Ratio

- Indicator of Rail "Rollover" Potential
- Concern Threshold: 0.5 to 0.6*

•Wheel Set L/V Ratio

- Indicator of Track Panel Shift Potential
- Concern Threshold: 0.3 to 0.5*

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*"Criteria for High-Speed Curving of Rail Vehicles," ASME Paper 79-WA/RT-L2, F. E. Dean and D. R. Ahlbeck, Battelle, 7 August 1979.

Computer Code Inputs

The following three slides show the computer code inputs. The inputs are grouped into the three categories shown.

Computer Code Inputs

$\boxed{\text{Dynamics of Six-Axle Locomotives - DSL2}}$

- Locomotive Car Body & Truck Parameters
- Track Geometry Defects
- Operational Parameters

Locomotive Car Body and Truck Parameters

The locomotive car body and trucks are modeled through the hardware-oriented parameters shown on this slide. For a given locomotive an input data base can be established that eliminates the need to input all of the data for each run. We have set up data bases for the U30C, HTC (soft) and E8 locomotive trucks.

Locomotive Car Body and Truck Parameters

- Hardware-Oriented
  - Geometric Properties
  - Mass Properties
  - Suspension Properties: Stiffness
Damping
Friction, etc

  - Wheel/Rail Interface: Flangeway Clearance
Wheel Tread Conicity, etc

Track Geometry Defect Designation

This slide shows the input used to specify track geometry defects. The basic waveform used is a versine (1 - cos). The amplitude, wavelength and number of repetitive cycles are specified for each defect type. The user may superimpose up to 25 separate defects (of the same or different type) to form complex waveforms.

C-2

Track Geometry Defect Designation

- <u>May Be Independently Superimposed</u>

Types:	Cross-Level Lateral (Alignment) Vertical (Surface) Gauge (Dynamic Variations)	Basic Waveform Is Versine
Parameters:	Amplitude Wavelength Number of Repetitive Defects	For Each <u>Type</u> Selected

Operational Parameters

The user supplies the operational inputs shown on the slide to define the locomotive state before it encounters the track geometry defects.

Operational Parameters

•Steady-State Condition Prior to Transient Response

- Locomotive Speed, mph
- Nominal Track Curvature, deg
- Nominal Track Superelevation, in.
- Tractive Effort, lb
- Lateral Wind Load, lb
- Lateral Coupler Force, lb

Computer Code Outputs

Code output consists of the items listed on the slide. For each case run the input data are listed, including (1) locomotive car body and truck geometry, mass properties, and suspension parameters, (2) track geometry defect specifications, and (3) steady-state operational parameters.

In a given run a locomotive speed range and speed increment may be specified facilitating evaluation of trends as a function of locomotive speed. For each speed a safety evaluation summary is printed listing peak values and times of occurrence for the calculated L/V ratios.

Two optional outputs are available. Time history plots can be generated for any of 259 variables including the locomotive state variables and all suspension system and wheel/rail interaction forces. All system variables can be printed at a given time to provide a snapshot of the code calculations for checkout or detailed analyses.

Computer Code Outputs

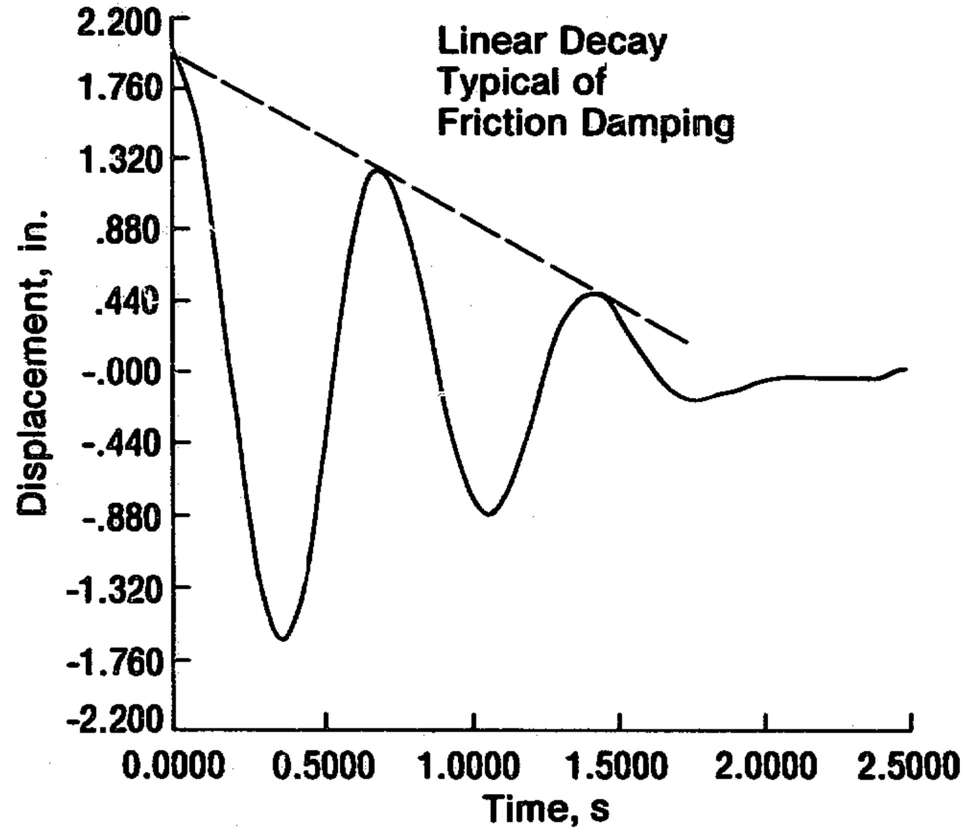
- List of Input Data
- Safety Evaluation Summary: Peak Values and Time of Occurrence
- Time History Plots of Selected State Variables: Optional
- "Snapshot" of System Variables: Optional

Sample Output

This slide shows an example plot of locomotive vertical displacement versus time. In the case shown, the car body was given an initial vertical displacement of approximately 2 inches and released. The resultant displacement time history is shown. The linear decay characteristic exhibited is typical of friction-damped systems. This particular plot was generated during code checkout.

Sample Output

Free Damped Response/ Locomotive Body Vertical

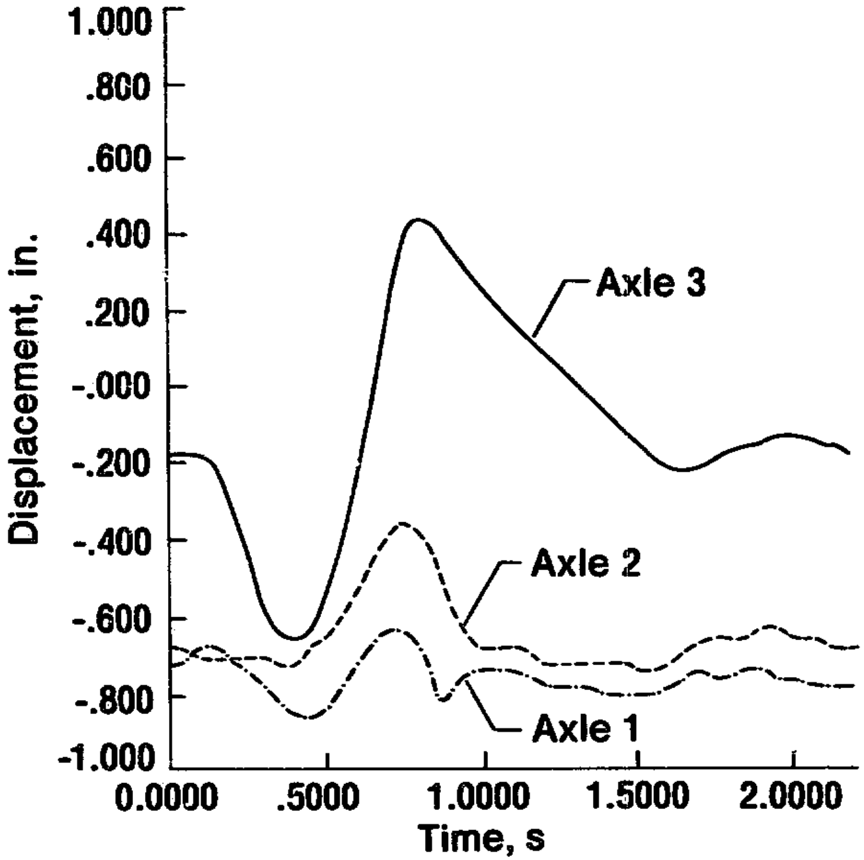


Sample Output

This slide shows an example plot of wheel set (trailing truck) lateral displacement from track centerline for a locomotive subjected to a combined track geometry defect at 54 mph. Axle 3 is the trailing axle on the trailing truck.

Sample Output

Wheel Set Lateral Displacement from Track Centerline (Combined Defects, 3-deg Curve, 54 mph)



Methodology Applications

Two studies were performed to demonstrate application of the nonlinear simulation computer code. A parameter sensitivity analysis was performed in the first study using the SDP-40F locomotive. The objective was to determine the relative importance of various parameters to operational safety.

The second study was a comparative analysis of three different locomotives--SDP-40F, U30C, E8. All three locomotives were subjected to the same set of rail geometry defects and performance was compared.

Methodology Application

Application of the Methodology Was Demonstrated in Two Phases

- <u>Sensitivity Analysis</u>

  Determine Relative Importance of Individual Parameters
  - Locomotive Parameters
    (e.g., Suspension Characteristics)
  - Track Geometry Defects
    (e.g., Amplitude, Wavelength)
  - Operational Parameters
    (e.g., Curvature, Speed, Tractive Effort)

- <u>Comparative Analysis</u>

  Estimate Relative Safety Performance of Different Locomotives
  - SDP-40F with New HTC Truck
  - U30C
  - E-8

Sensitivity Analysis

This slide delineates the procedure used in performing the SDP-40F sensitivity analysis. The baseline locomotive was equipped with new HTC (soft rubber suspension springs) trucks. Simulations were performed on curved track at 65 mph. An idealized track geometry defect based on Class 4 track standards was used.

The procedure was to vary one parameter at a time. The range of parameter variation was selected to represent the variation that might be found in railway service or that might be achieved within the existing design. Twenty-one parameters were evaluated. The variation in the measures of safety (L/V ratios) versus parameter value were plotted.

Sensitivity Analysis

Reference Conditions

- SDP-40F Locomotive with New HTC Trucks
- Curved Track
  (3-deg Curve, 6-in. Superelevation)
- Nominal Passenger Train Speed - 65 mph
  (3-in. Superelevation Deficiency)
- 9000 lb of Tractive Effort)
- Idealized Class 4 Track Geometry Defects

Vertical, Outer Rail:	2 in. Down	Combined Single-Pulse 78-ft Wavelength
Vertical, Inner Rail:	3/4 in. Down	
Lateral, Both Rails:	1 ½ in. to Outside of Curve	

Procedure

- Vary Parameters One At a Time

Evaluation

- Peak Value of Measures of Safety Occurring Within a Complete Run on Any Wheel, Wheel Set or Truck

Parameter Sensitivity Overview

This slide summarizes the results of the sensitivity analysis. The parameter influence was categorized as small (S), medium (M), or large (L). Categorization was based on the change in L/V ratios observed. The following three slides show some typical sensitivity analysis trend plots.

Parametric Sensitivity Overview

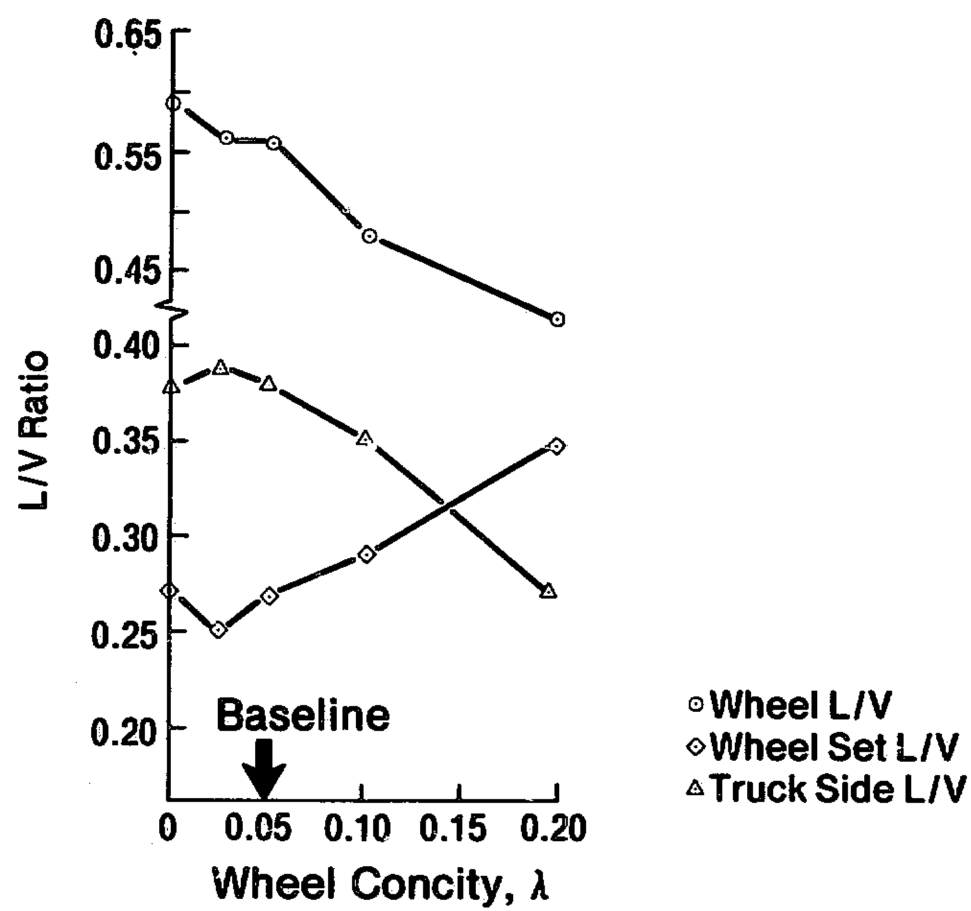
Parameter	Influence (Large, Moderate, Small)
• Track Geometry Defect	
Amplitude	L
Wavelength	L
Number of Cycles	L
• Wheel Rail Interaction	
Wheel Tread Conicity	L
Flange Clearance	S
Adhesion	M
Lateral Rail Stiffness	S
Tape Size Mismatch	L
• Primary Suspension	
Vertical Stiffness	M
Vertical Spring Travel	M
Pedestal Friction	S
External Hydraulic Dampers	M
Lateral Roller Bearing Freeplay	S/M
Center Axle Diameter Oversize	M
• Secondary Suspension	
Lateral Stiffness	M
Lateral Travel	M
Lateral Hydraulic Dampers	M
Center Plate Rotational Friction	S
• Operational Parameters	
Tractive Effort	S
Curvature	M

Influence	$\Delta L/V$
S	<0.05
M	0.05 to 0.10
L	>0.10

Computed Sensitivity to Wheel Conicity

Wheel conicity, center-axle mismatch, and wheel side-to-side mismatch were studied to evaluate the effect of wheel set geometry. Both wheel conicity and wheel side-to-side mismatch have large influences on the L/V ratios because these parameters directly affect the creep forces at the wheel. This slide shows a plot of L/V variations as wheel conicity is varied from 0.0 to 0.20. The arrow denotes the baseline conicity (0.05).

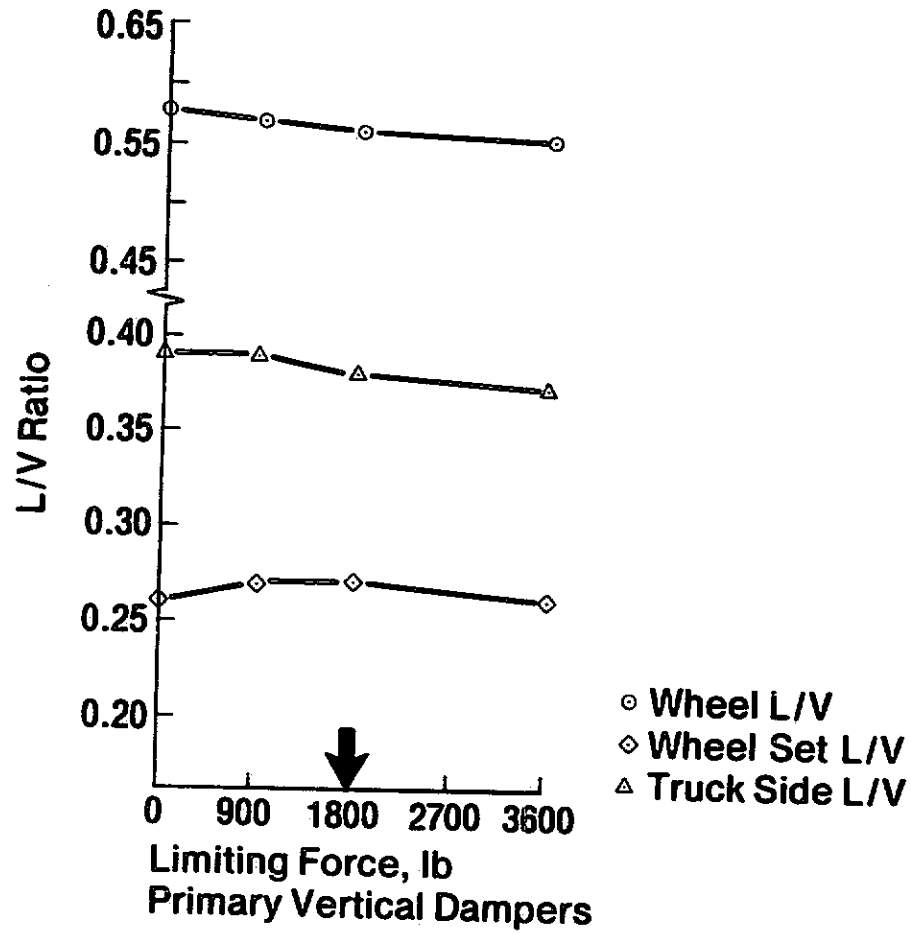
Computed Sensitivity to Wheel Conicity



Computed Sensitivity to Primary Vertical Dampers

This slide shows the sensitivity of L/V to the limiting force assumed in the primary vertical dampers (external hydraulic shock absorbers). The variation shown is small; however, due to the baseline 9000-pound tractive effort the results are misleading. Friction damping probably overwhelms any effects. The next slide illustrates this fact.

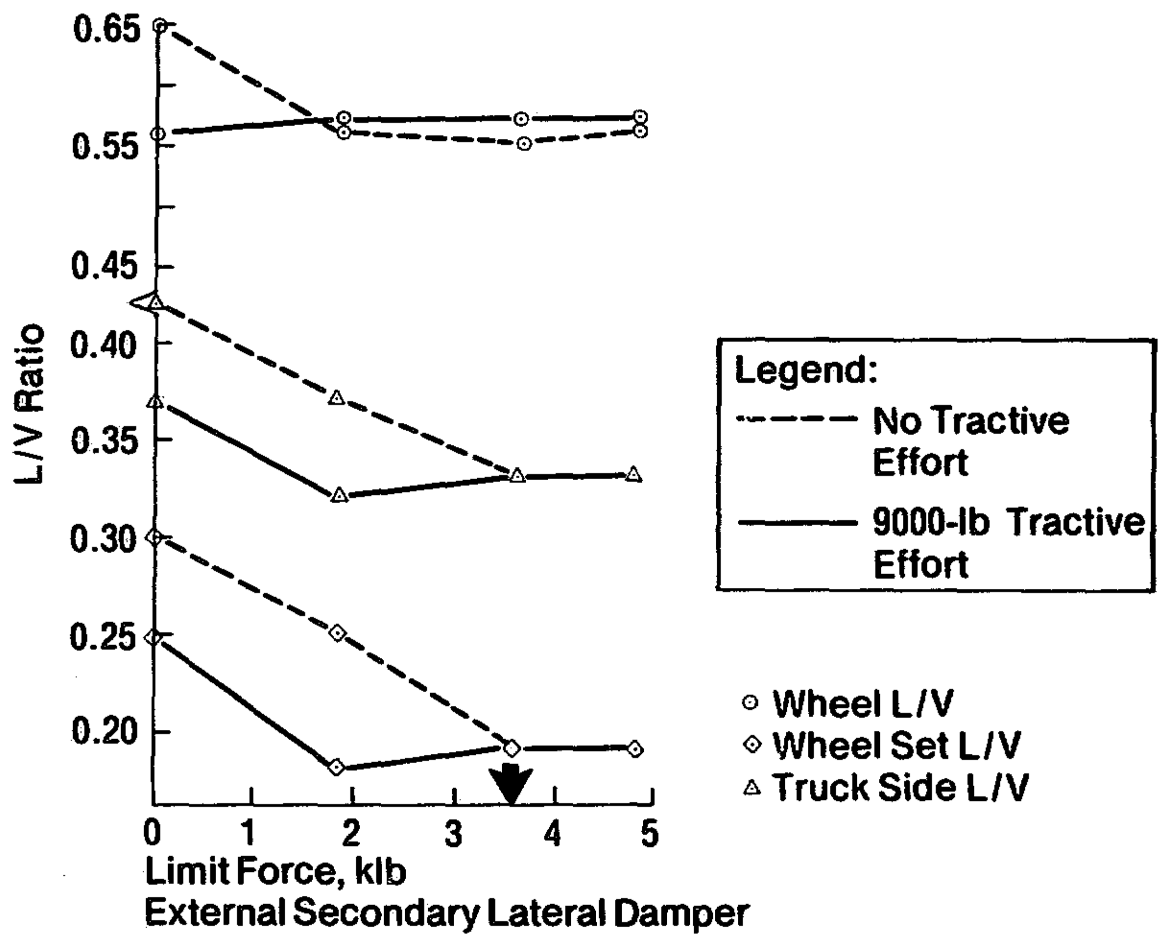
Computed Sensitivity to Primary Vertical Dampers



Computed Sensitivity to Secondary Lateral Dampers

New HTC trucks contain a hydraulic shock absorber in the lateral secondary suspension. This slide shows L/V sensitivity to a variation in the limit force of this damper. With the baseline tractive effort (9000 lb), the sensitivity is moderate. However, when the tractive effort is set to zero, the sensitivity is large because friction damping in the truck is a direct function of the tractive effort.

Computed Sensitivity to Secondary Lateral Dampers



Sensitivity Study Conclusions

This slide highlights some of the key findings in the sensitivity analysis. Note, however, that the analysis performed is very limited and was designed to demonstrate the versatility of the code. The capability exists to do a rigorous evaluation of locomotive parameters for a variety of track geometry and operational conditions, providing the user community with a powerful analytical tool.

Sensitivity Study Conclusions

<u>Effects on Measures of Safety</u>

- Characteristics of Track Geometry Defect Most Significant of Parameters Considered
- Lateral Defect More Significant Than Cross-Level and Vertical
- Locomotive Response Dependent on Suspension Damping
- Locomotive Response Sensitive to Wheel Diameter Mismatch

Comparative Analysis

The second study performed was a comparative analysis of three locomotives--SDP-40F (new HTC trucks), U30C, E8. The analysis was performed on a simulated 3-degree curve over a speed range of 40 to 65 mph. A combined (vertical, lateral, cross-level) track geometry defect was embedded in the curve:

Vertical, outer rail = 2 inches down;
Vertical, inner rail = 3/4 inches down;
Lateral, both rails = 1 1/2 inches to outside of curve.

Both 78- and 39-foot defect wavelengths were evaluated. The objective of this study was to demonstrate code capabilities and not necessarily to provide a rigorous comparison of the three locomotives.

The following three slides present the comparative results for the 78-foot wavelength defect.

Comparative Analysis

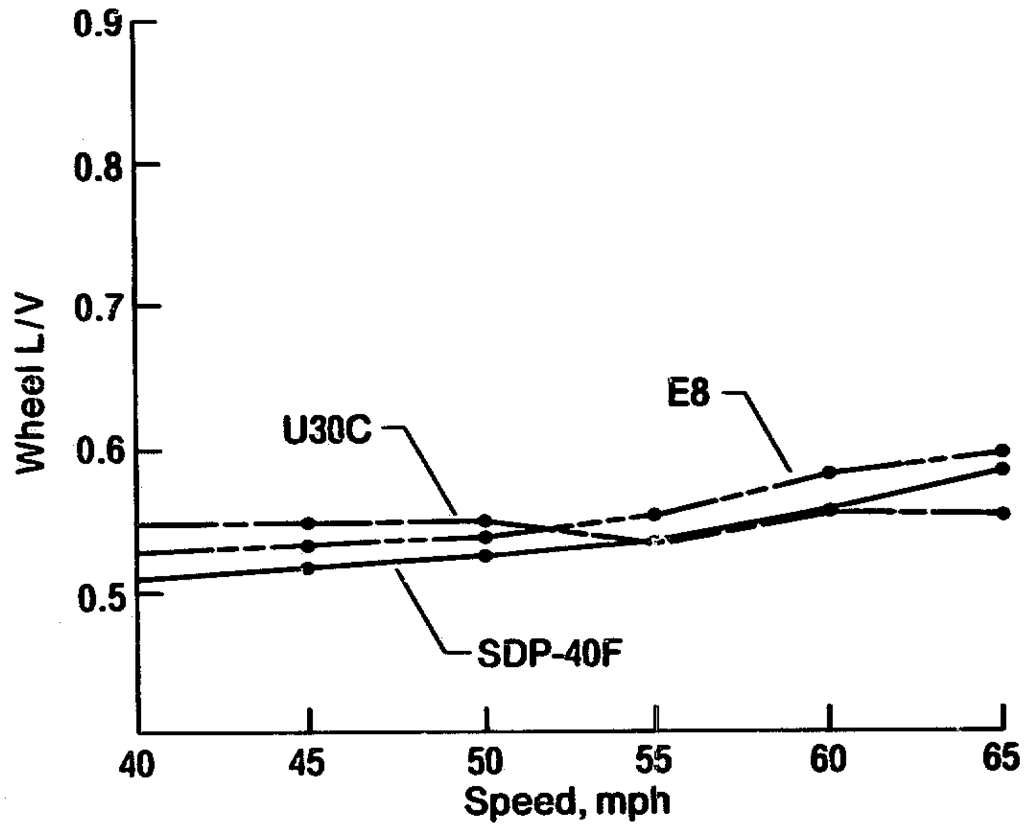
- Suspension Parameters Derived from Test Data
- Analytical Comparison of Three Locomotives
  - SDP-40F (New HTC Trucks)
  - U30C
  - E8
- Used Combined Track Geometry Defect (Vertical, Lateral, Cross-Level)
  - Considered Single Pulses (78- and 39-ft Wavelengths)
- Operational Parameters
  - 3-deg Curve, 6-in. Superelevation, 40 to 65 mph, 9000-lb Tractive Effort

Peak Wheel L/V Ratio

Wheel L/V is an indicator of flange climbing potential. There are only minor differences between the three locomotives. All wheel L/V ratios are well below critical values, indicating a low probability of derailment due to flange climbing for the track defect analyzed.

Analytical Comparative Analysis

Peak Wheel L/V Ratio
Combined Defects - 78-ft Wavelength



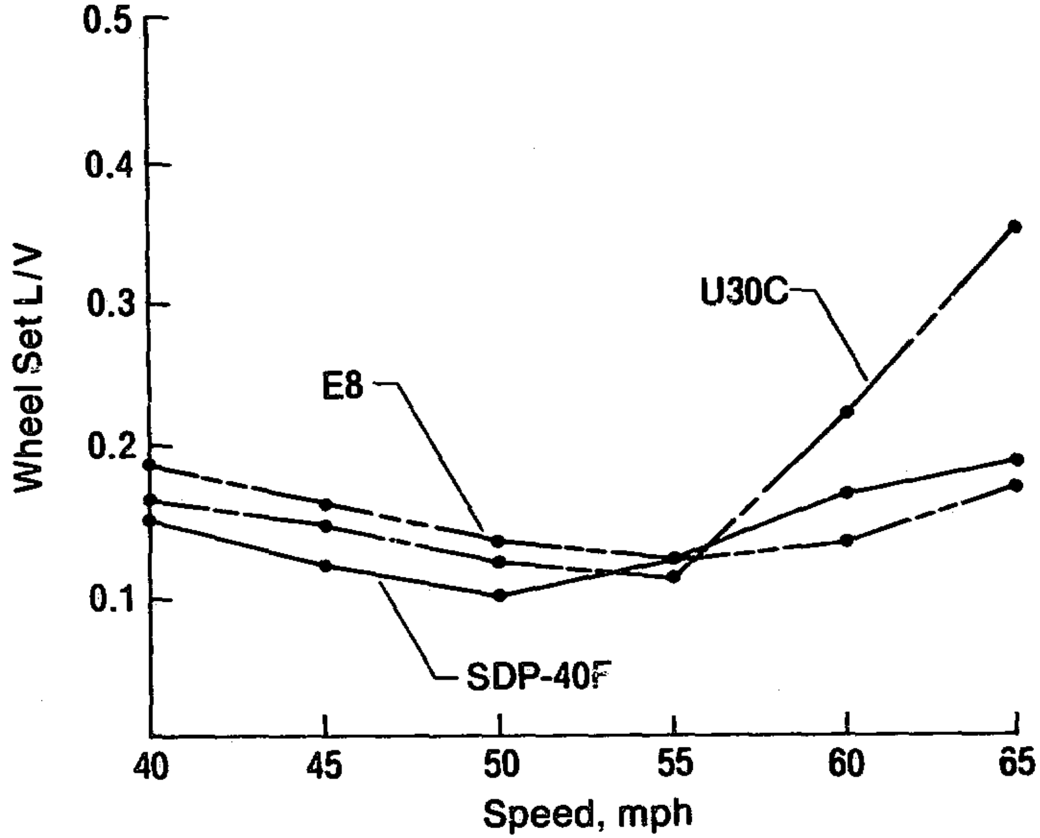
Peak Wheel Set L/V Ratio

Relatively large differences are seen in this slide when comparing wheel set L/V (an indicator of track panel shift potential). At 65 mph the U30C produces peak values nearly twice as high as the other two locomotives. This peak value occurred on the trailing axle of the trailing truck.

Analytical Comparative Analysis

<u>Peak Wheel Set L/V</u>

Combined Defects—78-ft Wavelength

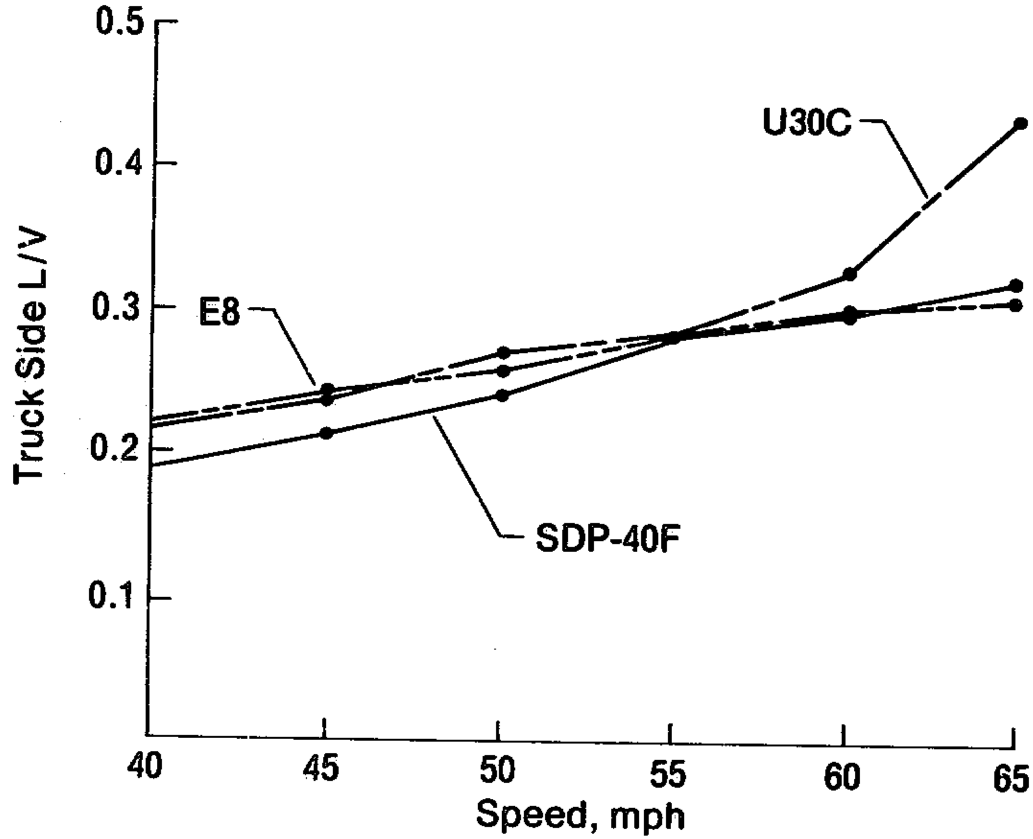


Peak Truck Side L/V Ratio

This slide shows a trend similar to the last slide. At 65 mph the U30C exhibits a significant increase in truck side L/V. Truck side L/V is an indicator of rail rollover potential.

Analytical Comparative Analysis

<u>Peak Truck Side L/V Ratio</u>
Combined Defects-78-ft Wavelength



Comparative Analysis Conclusions

In general the peak values of the safety evaluators for all three locomotives are similar. At high speeds (65 mph), however, the U30C exhibits greater wheel set and truck side L/V ratios. A sensitivity evaluation of the U30C was performed to try and determine why this occurs. In this evaluation, the SDP-40F and U30C parameters were compared. The parameters significantly different between the two locomotives (approximately 50% difference) were varied in the U30C analysis to determine response sensitivity. It was found that the addition of a lateral shock absorber in the secondary suspension of the U30C (similar to that found in the SDP-40F) reduces the L/V ratios by approximately 25% at 65 mph.

The comparative analysis performed was very limited and only demonstrates code capability. The intent was not to totally evaluate the performance of the three locomotives analyzed.

Comparative Analysis Conclusions

Analytical Comparison of Three Locomotives

- Peak Value of Safety Evaluators Similar for All Three Locomotives
- U30C Exhibits Significantly Greater Wheel Set and Truck Side L/V at 65 mph: Potential Track Panel Shift
- Sensitivity Analysis Indicates That U30C Wheel Set and Truck Side L/V (at 65 mph) Can Be Reduced by $\approx 25\%$ by Adding a Lateral Damper

Potential Applications

This slide presents some potential applications of the analytical methodology developed under this contract. We feel the code has general applicability in the design, maintanence, and operational evaluation of locomotives. The code can be used to supplement, and in some cases replace, expensive field testing.

Potential Applications

The Methodology Can Be Used As a Predictive Technique in the Determination of:

- Maximum Operating Speeds
- Critical Track Geometry Defects
- Minimum Track Strength Requirements
- Appropriate Locomotive Maintenance Standards
- Derailment Mechanisms
- Mechanical Design of Locomotive Suspension Components
  - Design Loads
  - Suspension Characteristics
- Design Modifications for Existing Locomotives

Project Summary

This slide summarizes the accomplishments of this project.

A methodology that allows the testing of a locomotive truck as a system has been developed and refined. The testing methodology has been used to characterize eight locomotive trucks currently in service to form the core of an expandable data base.

An analytical tool that uses the truck test data and simulates the non-linear response of locomotives to track geometry defects has been developed. Through the calculation of selected safety parameters, locomotive operational safety/performance can be evaluated. The analytical methodology has been demonstrated through a sensitivity analysis of the SDP-40F locomotive and a limited comparative analysis of three operational locomotives.

Project Summary

- Truck Test Data Base Established: 8 Trucks
- Testing Methodology Has Been Refined
- Analytical Tools Have Been Developed to Evaluate Operational Safety
- Sensitivity Analysis Conducted on Truck Parameters